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[*Continued on page (III) of Cover.*

THE DEVELOPMENT OF THE SINGLE-BREAK OIL CIRCUIT-BREAKER FOR METALCLAD SWITCHGEAR

By D. R. DAVIES, Member, and C. H. FLURSCHEIM, B.A., Associate Member.

(*Paper first received* 3*rd July*, 1935, *in amended form* 13*th December*, 1935, *and in final form* 22*nd May*, 1936; *read before* THE INSTITUTION 20*th February, before the* TEES-SIDE SUB-CENTRE 17*th February, before the* NORTH-EASTERN CENTRE 24*th February, before the* NORTH-WESTERN CENTRE 25*th February, and before the* SOUTH MIDLAND CENTRE 9*th March*, 1936.)

SUMMARY

The theoretical considerations in the choice of number of breaks are analysed and it is shown that, while for plain breakers multi-break construction may have its advantages, the more efficient the arc-control devices employed the less the advantages of additional breaks become with normal designs. In particular, it is shown that for a metalclad and cable system, the duty on one break of a multi-break controlled-arc breaker is almost as great as for that of a single-break unit. Experimental evidence in support of the theory advanced, obtained with cathode-ray equipment, is given.

The development of a single-break 66-kV metalclad equipment is described, with particular reference to the interrupting ability, and test-results are given, obtained on four different short-circuit plants, showing consistent operation. The advantages to the user of the single-break oil circuit-breaker are shown by comparison with double-break designs of similar rating, and single-break layouts are described for different switching schemes and system voltages.

In the Appendix an analysis is made of 3-phase cathode-ray films, showing that no leakage current is carried and that in consequence the observed reliable operation is to be expected.

HISTORICAL

The single-break oil circuit-breaker is not new in conception, as early designs by Dr. Ferranti were, in fact, of this type, as also were later American breakers due to E. M. Hewlett. With plain oil circuit-breakers or relatively inefficient explosion contacts as then used, however, interruption was largely dependent on length of arc, and, since a long total break is more readily obtained, from mechanical considerations, in a multi-break switch, this form superseded the single-break construction.

With the advent of modern arc-interrupting devices in which only comparatively short arc lengths are necessary to clear all types of faults, it is reasonable to return to the single-break layout if simplification can be effected thereby. This has been done by several foreign manufacturers when developing new types of breakers, notably oil impulse, expansion, and gas-blast types, and also by the Electrical Research Association in experimental breakers operating on similar principles. The advantages of metalclad construction and oil insulation have hindered the adoption of these types in this country, as they are all difficult to incorporate in metalclad equipments. The company with which the authors are associated has, however, developed single-break high-voltage metalclad breakers with one cross-jet pot in each phase, the satisfactory operation of which has been proved by test and service conditions.

THEORETICAL CONSIDERATIONS IN THE CHOICE OF NUMBER OF BREAKS IN SERIES

With a breaker having several gaps in series in one phase, the power current flowing through each must be equal, and the distribution of interrupting duty between them can therefore only be controlled by the recovery and restriking voltages appearing across each arc.

The voltage distribution across the gaps when a potential difference is impressed on the breaker terminals and no arcing occurs, is controlled solely by the capacitances between the various contacts, between contacts and earth, and by the voltages to earth of the terminals. Fig 1(*a*) represents an assumed double-break unit of typical proportions, in which the capacitances across the gaps are one-quarter that of cross-bar to earth at the position where interruption occurs. If one pole is earthed by a short-circuit and a voltage is applied to the other terminal of 100 volts, 83·3 volts will appear across the line-side gap and only 16·7 across the second gap. Considering, therefore, this breaker clearing an earthed fault, 83·3 per cent of the recovery voltage would appear across the line gap if no modifying factors existed.

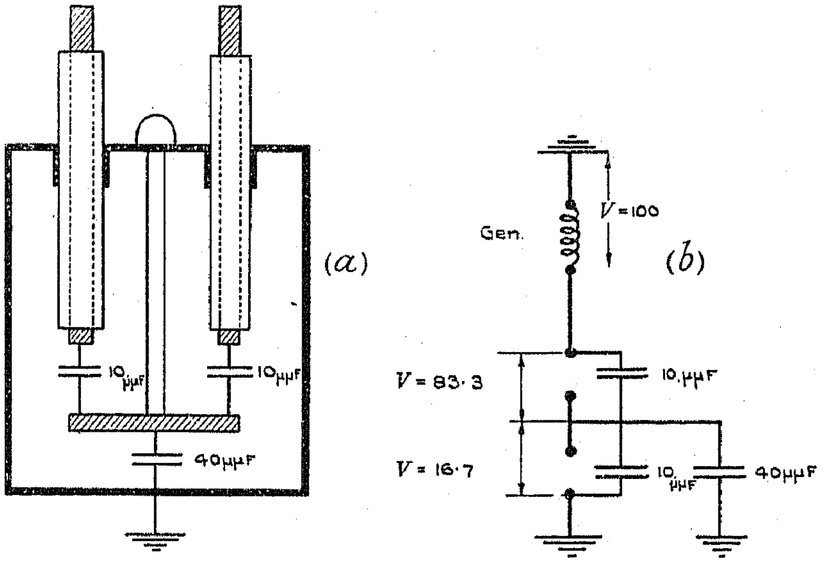


Fig. 1.—Typical double-break circuit breaker, and capacitance distribution.

Restriking-voltage rates of rise are proportional to the natural oscillating frequency and the recovery voltage, and will therefore be distributed across the breaks in a similar proportion. The duty per break of a perfect circuit interrupter of this design, in which post-arc effects could be neglected, would therefore be divided

Table 1

CAPACITANCE-CONTROLLED VOLTAGE DISTRIBUTION FOR TYPICAL BREAKER IN A SYSTEM WITH PHASE-TO-PHASE R.M.S. RECOVERY VOLTAGE OF 122 VOLTS

Type of fault	Type of system								
	Solidly-earthed neutral			Impedance-earthed neutral			Insulated neutral		
	Double break	Single break	% of duty performed by 2nd break	Double break	Single break	% of duty performed by 2nd break	Double break	Single break	% of duty performed by 2nd break
Earthed faults:—									
3-phase; 1st phase to clear	83·4 16·6	100	16·6	125 25	150	16·6	125 25	150	16·6
Phase-to-phase; phases clearing simultaneously	83·4 16·6	100	16·6	between {83·4 16·6 {72·0 14·6	100 } 86·6}	16·6	72·0 14·6	86·6	16·6
Phase-to-phase; 1 phase remaining conducting*	83·4 16·6	100	16·6	144·0 29·0	173	16·6	144·0 29·0	173	16·6
Phase to earth	83·4 16·6	100	16·6	<83·4 <16·6	<100	16·6	— —	—	—
Unearthed faults:—									
3-phase; 1st phase to clear	91·6 58·3	150	39	91·6 58·3	150	39	Indeterminate total 150	150	Indeterminate
Phase-to-phase; phases clearing simultaneously	72·0 14·6	86·6	16·6	72·0 14·6	86·6	16·6	Indeterminate total 86·6	86·6	Indeterminate
Phase-to-phase; 1 phase remaining conducting*	86·6 86·6	173	50	86·6 86·6	173	50	Indeterminate total 173	173	Indeterminate

* These assume that one phase of breaker remains conducting for an appreciable finite time after the other phase has interrupted the arc, a very improbable event in efficient controlled-arc breakers but possible with plain-break breakers.

very unequally, and the omission of the second gap would increase the work, or dielectric stress, of the first by only 20 per cent. Experimental measurement on a model has confirmed this order of capacitance voltage distribution.*

Actual faults on a 3-phase system may be of a variety of forms, and the systems themselves will vary in the method of neutral earthing.

Table 1 gives instantaneous values of the capacitance-controlled 50-cycle voltage appearing across each gap on interrupting symmetrical currents in a purely reactive circuit, for a 2-break and equivalent single-break unit, with different types of faults and systems.

Considering the normal large British metalclad and cable systems having phase separation, and in which, therefore, unearthed faults cannot occur, it will be seen that it is necessary to design each break of a double-break unit to be capable of interrupting about 84 per cent of the total voltage and rate of rise which must be cleared by an equivalent single-break unit. Even when unearthed faults can occur, the second break does not perform more than 39 per cent of the total duty with controlled-arc breakers, while the worst possibility—that of earthed faults—must still be allowed for in the design, if the neutral is not solidly earthed.

It may be asked, therefore, how double-break or multi-break construction, in which the voltage distribution will be even less favourable, can be justified. The answer depends on the modifications in capacitance-controlled voltage distribution which may be made by transient post-arc effects as discussed below.

While the arc current is flowing, the voltage across each break of a multi-break unit will be sensibly equal, since the arc acts as a low-resistance shunt and will entirely swamp the capacitance currents which control the static distribution. If at the final current zero the arc resistances suddenly become infinite, then their influence as a grading factor will cease; but if, as can occur, they all retain a finite resistance for an appreciable time during this period, their shunting effect will continue and will modify not only the restriking waveform—a fact which has been previously analysed†—but also the voltage distribution across the gaps. Since this effect will tend to even-out the duty, it is to be expected that breakers permitting appreciable leakage-current flow will benefit by increased numbers of breaks more than those which eliminate all flow immediately after the zero.

A second modifying factor has been suggested‡ as being due to the "space charge effect." It is known that the flow of current in a hot gas is chiefly due to a negative electron drift. The positively charged atoms are relatively immobile, and will tend to concentrate near the cathode. Thus when arcing ceases there will be a positive space charge near the cathode terminal, and this will affect the voltage distribution across the one gap. In addition it will delay the build-up of the capacitance-controlled static voltage distribution across series gaps. The degree of this latter effect has not, it is believed, been published, but it must be very slight if the residual conductivity and ionization at interruption are low.

EXPERIMENTAL TEST OF THEORY

Tests were carried out with the aid of a 3-phase cathode-ray oscillograph* in order to verify the above reasoning. Two sets were made, in the first of which the true distribution was considerably modified by the measuring circuit, and in the second of which the distortion due to this cause was of a negligible value.

Series I.

These tests were made on an 11-kV metalclad breaker with the cathode-ray oscillograph connected as in Fig. 2, the voltages measured being those across the entire breaker (or two arcs) and from the moving contact to earth.

The normal voltage distribution of the 11-kV breaker, of approximately 15 per cent on the shielded gap, was reduced to 2 per cent by the addition of the large capacitance of the standard test-plant voltage-divider and connecting leads, totalling 2 400 $\mu\mu$F. It was, however, considered that although these tests would not be quantitatively correct for a normal breaker, if the percentage voltage distribution obtained agreed with the predicted value in the distorted case it would be a reasonable deduction that it would also agree for the undistorted case.

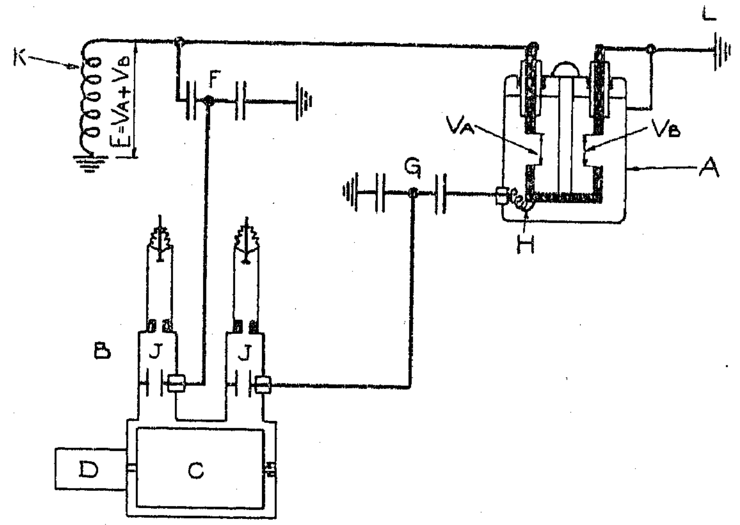


Fig. 2.—Schematic diagram of cathode-ray connections.

A = Test breaker.
B = Cathode ray (2 phases of 3-phase instrument).
C = Rotating drum film.
D = Motor.
F = Capacitance voltage divider for cathode-ray tube measuring voltage across breaker ($V_A + V_B$).
G = Do. do. across earth-side gap (V_B).
H = Flexible connector from moving contact to divider.
J = Deflection plates.
K = Generator (tests 1–10) or Transformer (tests 11–14).
L = Earthed fault.

Fig. 3 shows typical curves drawn from cathode-ray films of the tests made (Nos. 2, 3, 4, and 6). Fig. 4 (Plate 1, facing page 144) is the cathode-ray oscillogram of test No. 2, and an analysis of all tests is given in Table 2. It will be observed that in the cases where cross-jet pots were fitted, the restriking oscillations across the whole breaker were those attributable to the true circuit without leakage-resistance damping subsequent to the final zero. The oscillations across the second gap were only 2 to 3 per cent of those across the breaker, showing close agreement with the estimated values.

---

* See Reference (1). † *Ibid.*, (2) and (3). ‡ *Ibid.*, (4).

* See Reference (5).

In all cross-jet tests there was some residual charge on the moving contact of a relatively small value which affected the peak voltages by a few per cent, except in test No. 6, when an appreciable charge was left. This was, however, of the same polarity as the arc voltage itself, and the second break in this instance actually hindered the action of the first to the extent of increasing the voltage peaks and rates of rise across it by over 50 per cent above the applied system values.

Tests Nos. 4 and 5 were made on the same breaker and with circuit connections as for tests Nos. 2 and 1 respectively, except that the cross-jet plates were removed, converting it to the open-arc plain-break type. Considerable leakage current occurred at the final zero in both tests, damping out the high-frequency oscillations and grading the distribution of voltage as predicted. Fig. 5 (Plate 2) is an oscillogram of test No. 4 and is therefore comparable with Fig. 4.

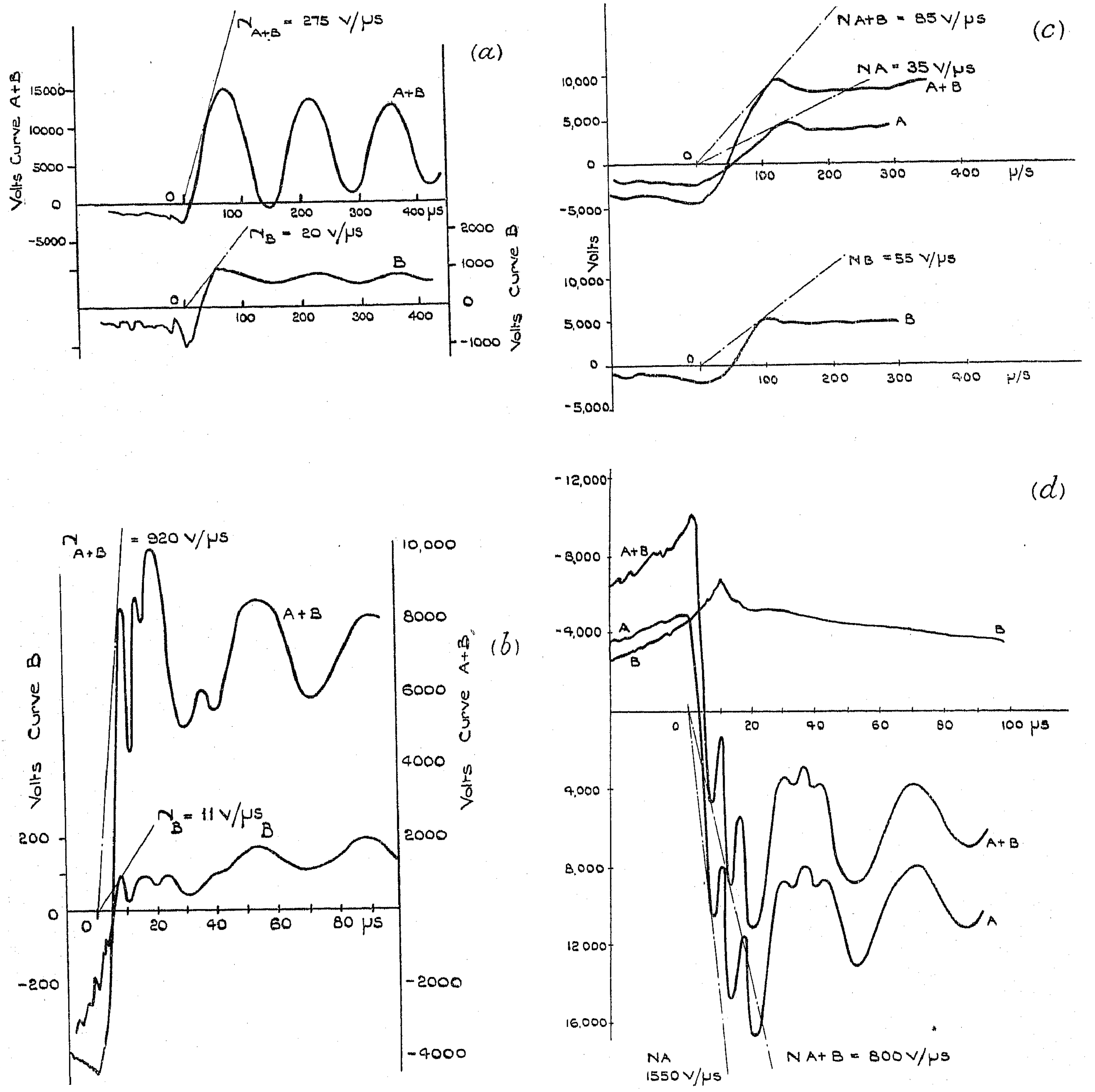
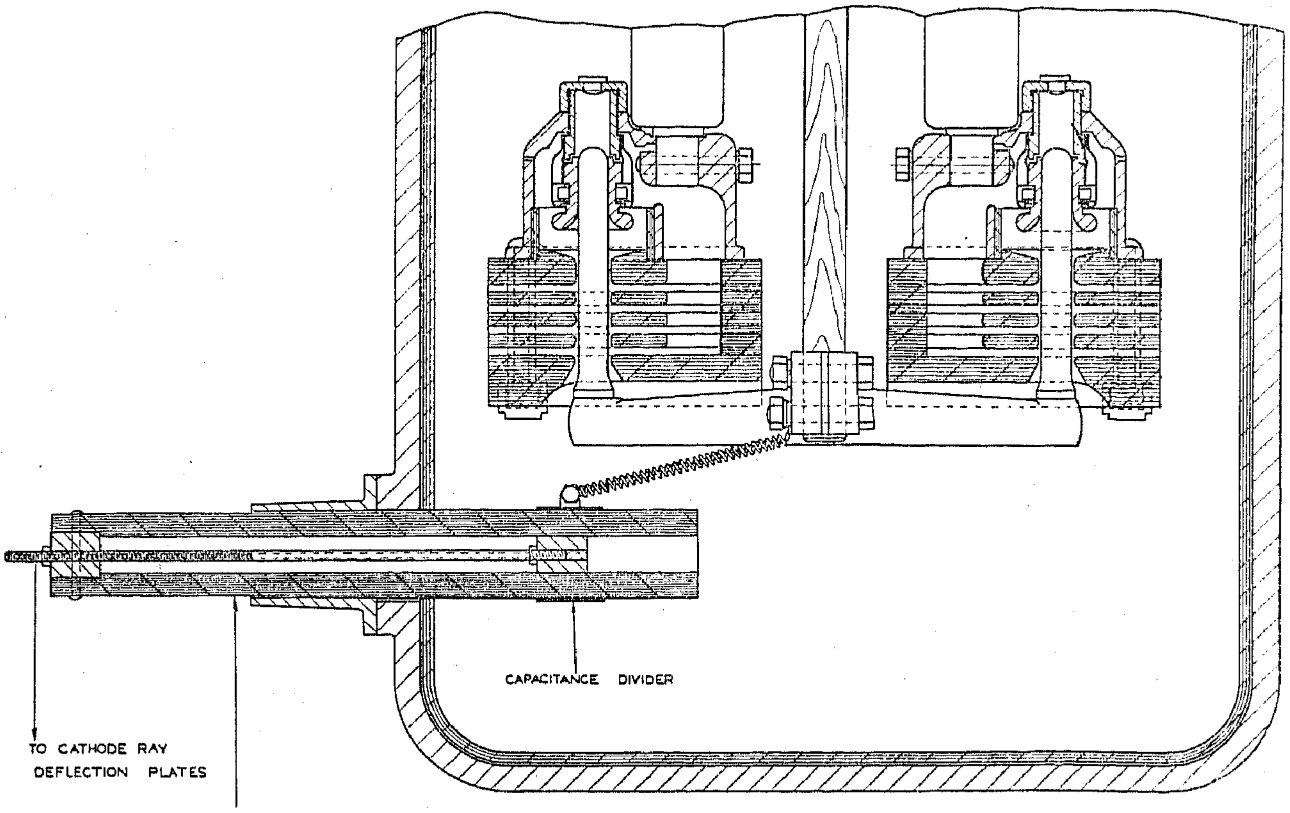


Fig. 3

(a) Test No. 2. Cross-jet contacts.
4 570 amps. (r.m.s.).
(b) Test No. 3. Cross-jet contacts.
14 900 amps (r.m.s.).

(c) Test No. 4. Plain break.
4 580 amps. (r.m.s.).
(d) Test No. 6. Cross-jet contacts.
18 700 amps. (r.m.s.).

The advantage of grading which may be obtained from arc resistance by this class of multi-gap breaker as compared with controlled-arc breakers is more than than with a single break, while, conversely, if it is efficient the second arc will not take a fair share of the restriking voltage.



Note.—This bushing is situated in front of the lifting rod to allow the correct travel.

Fig. 6.—Capacitance voltage-divider assembled in double-break oil circuit-breaker.

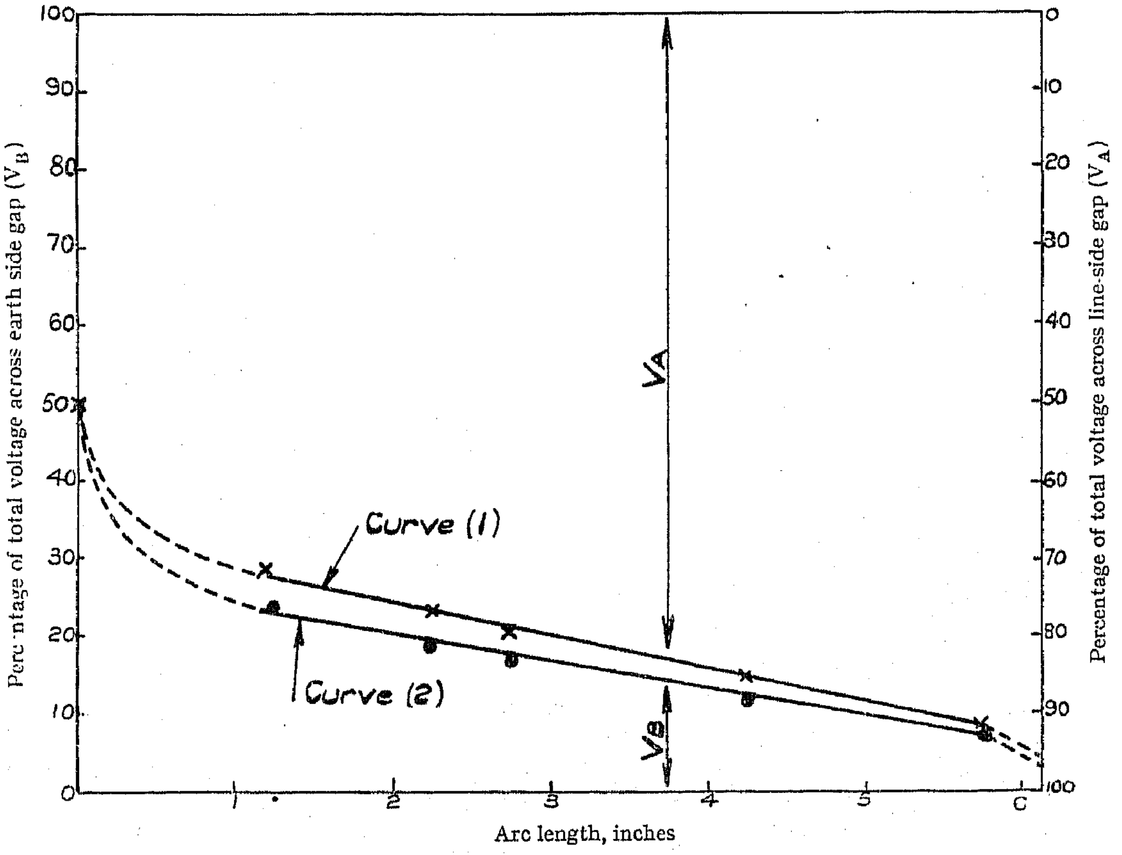


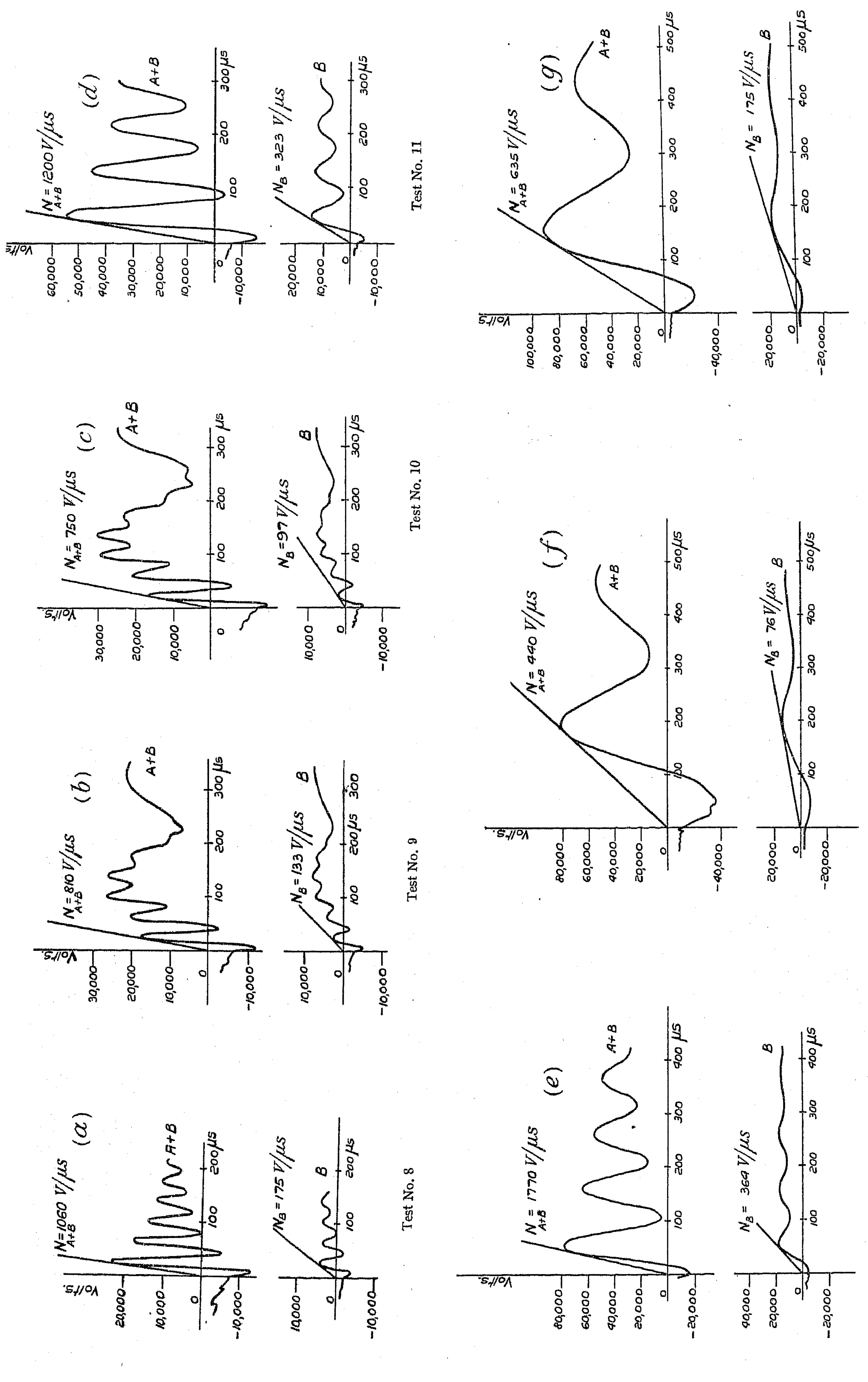
Fig. 7.—Distribution of duty over double-gap 33-kV breaker, calculated from capacitance measurements.

Curve (1).—Breaker alone.
„ (2).—Breaker with capacitance divider connected.

offset by the erratic behaviour consequent on leakage current—long arc lengths and durations, with their attendant mechanical and dielectric troubles. Nevertheless, a plain breaker, if it is inefficient enough to permit this leakage, will be better off with multi-breaks

Series II.

A second series of tests were made on a 33-kV metalclad breaker fitted with a specially constructed capacitance divider, which increased the capacitance to earth of the moving contact by only 12 $\mu\mu$F. This was made



Test No. 8 Test No. 9 Test No. 10 Test No. 11

Test No. 12 Test No. 13 Test No. 14

Fig. 8.—Curves showing distribution of restriking voltage for Series 2 tests.

Table 2

Test No.	R.M.S. current (initial) in arc	Single-phase r.m.s. recovery voltage	Arc duration ($\frac{1}{2}$-cycles)	Type of contact (cross-jet or plain break)	High-frequency peak restriking voltage across earth-side gap (V_B)	High-frequency peak restriking voltage across entire breaker (V_{A+B})	Observed rate of rise of restriking voltage across earth-side gap (N_B)	Observed rate of rise of restriking voltage across entire breaker (N_{A+B})	System natural oscillating frequency	Static charge observed on moving contact during first restriking oscillation	Percentage of high-frequency peak restriking voltage across earth-side gap ($100 \times V_B/V_{A+B}$)	Percentage of rate of rise across earth-side gap ($100 \times N_B/N_{A+B}$)
	amps.	volts			volts	volts	volts/microsec.	volts/microsec		volts		
1	4 520	5 500	4·7	C.J.	700	15 800	50	1 200	47 500	+ 300	4·4	4·1
2	4 570	5 500	3·0	C.J.	900	15 400	20	275	7 100	+ 600	5·8	7·3
3	14 900	6 050	2·05	C.J.	100	10 100	11	920	32 500 96 000	− 50	1·0	1·2
4	4 580	5 430	15·7	P.B.	5 600	9 500	55	85	7 100	+ 5 000*	58·2	64
5	4 420	5 360	16·3	P.B.	5 900	7 400	110	120	47 500	+ 5 700*	79·5	91
6	18 700	5 880	2·0	C.J.	− 5 600	11 200	0	800	29 500 110 000	− 5 800	− 50	0
7	27 400	6 370	2·0	C.J.	300	11 800	30	1 250	29 500 110 000	0	2·5	2·4

* Due to resistance grading.

Table 3

Test No.	R.M.S. current (initial) in arc	Single-phase r.m.s. recovery voltage	Equivalent 3-phase recovery voltage	Arc duration ($\frac{1}{2}$-cycles)	High-frequency peak restriking voltage across earth-side gap (V_B)	High-frequency peak restriking voltage across entire breaker (V_{A+B})	Observed rate of rise of restriking voltage across earth-side gap (N_B)	Observed rate of rise of restriking voltage across entire breaker (N_{A+B})	System natural oscillating frequency	Percentage of high-frequency peak restriking voltage across earth-side gap ($100 \times V_B/V_{A+B}$)	Percentage of rate of rise across earth-side gap ($100 \times N_B/N_{A+B}$)
	amps.	volts	volts		volts	volts	volts/microsec·	volts/microsec.			
8	2 720	6 300	7 250	3·3	4 600*	24 000	175*	1 060	26 200	19*	16·5*
9	2 470	11 100	12 800	2·5	8 100	26 600	133	810	4 200 25 000	30·5	16·5
10	2 620	11 100	12 800	2·9	7 970	30 300	97	750	4 200 25 000	26·2	13
11	1 890	18 400	21 300	3·3	15 100	55 200	323	1 200	12 300	27·2	27
12	2 050	28 700	33 200	3·9	18 500	79 200	364	1 770	9 400	23·3	20·5
13	358	29 100	33 600	4·1	14 200	82 000	76	440	3 700	17·3	17·1
14	514	36 700	42 500	4·5	19 500	90 200	111	635	3 700	21·6	17·5
15	7 270	32 300	37 300	4·96	7 900	95 200	170	2 350	13 900	8·3	7·25
16	5 460	26 000	30 000	3·94	21 000	59 500	490	1 380	13 900	36·3	35·5
17	7 000	31 600	36 500	3·64	29 300	95 200*	680	2 350*	13 900	30·7*	29

* These figures for tests Nos. 8 and 17 are approximate only.

possible by reducing the capacitance of the connection between divider and cathode-ray deflection plates, and by incorporating it in the breaker as shown in Fig. 6.

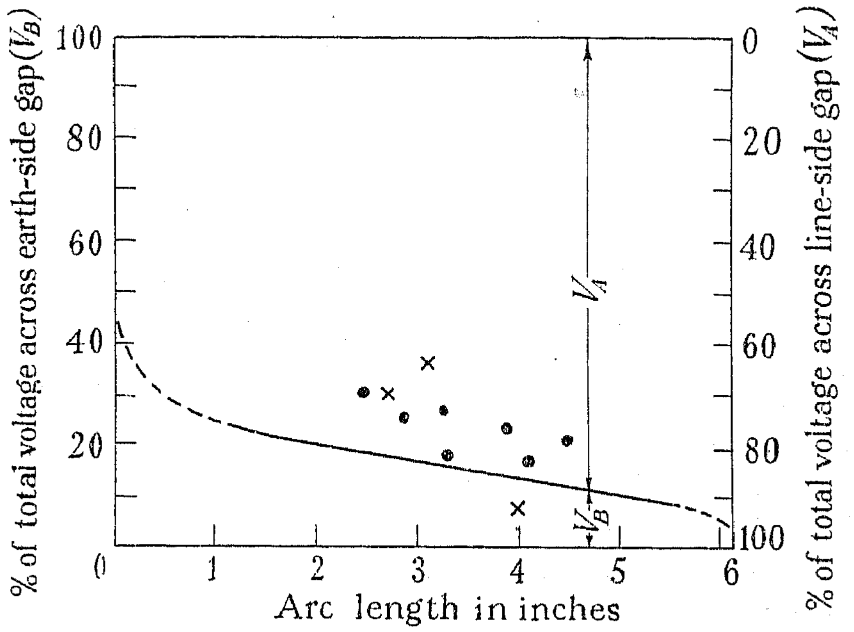


Fig. 10

● Tests made at 358–2 720 amps. (r.m.s.).
× Tests made at 5 460–7 270 amps. (r.m.s.).
Continuous curve represents theoretical distribution (including divider).

Table 4

THREE-PHASE TESTS ON DOUBLE-BREAK OIL CIRCUIT-BREAKER WITH CROSS-JET POTS

Tests with 2 breaks in series per phase				Tests with 1 break per phase and 1 break short-circuited out			
Recovery voltage (phase to phase)	Average r.m.s. current (initial) in arc	Individual arc length	Arc duration (½-cycles)	Recovery voltage (phase to phase)	Average r.m.s. current (initial) in arc	Arc length	Arc duration (½-cycles)
kV	amps.	in.		kV	amps.	in.	
21·5	3 050	2·64	3·4	15·4	2 100	2·95	4·0
22·1	2 850	3·3	4·4	16·3	2 440	2·95	4·1
22·4	3 320	3·3	4·2	18·3	2 820	3·05	4·2
23·7	3 770	2·64	3·6	21·4	3 230	3·05	4·1
23·1	3 720	2·64	3·6	23·8	3 000	3·05	4·15
26·8	4 080	2·8	3·7	25·2	3 380	3·3	4·45
26·8	4 120	2·47	3·4	26·6	3 430	3·3	4·3
27·2	4 470	3·14	4·0	27·4	3 660	3·3	4·25
27·2	4 100	3·3	4·1	28·9	4 120	3·3	4·5
AVERAGE VALUES							
24·6	3 710	2·9	3·83	22·6	3 120	3·13	4·24
				Percentage of double-break figures			
				92	84	108	111

The divider was constructed in the form of a bushing, the banding wire of which was connected by a flexible lead to the moving contact, while an inner and adjustable concentric cylinder was connected to the deflection plates. The various capacitances in the breaker were measured by means of a 5 000-volt Schering bridge, and in Fig. 7 are given curves calculated from these for voltage distribution over the gaps both with and without the divider, showing a negligible distortion.

In order to prevent any error due to direct pick-up of voltage from the high-voltage incoming cable, the low-voltage connection to the cathode-ray oscillograph was shielded, and a test made with this lead disconnected at the divider gave zero deflection. The readings obtained with the equipment are therefore correct within a few per cent.

The results obtained from these tests are given in Fig. 8 and are analysed in Table 3. Fig. 9 (Plate 3) is the cathode-ray oscillogram of test No. 13.

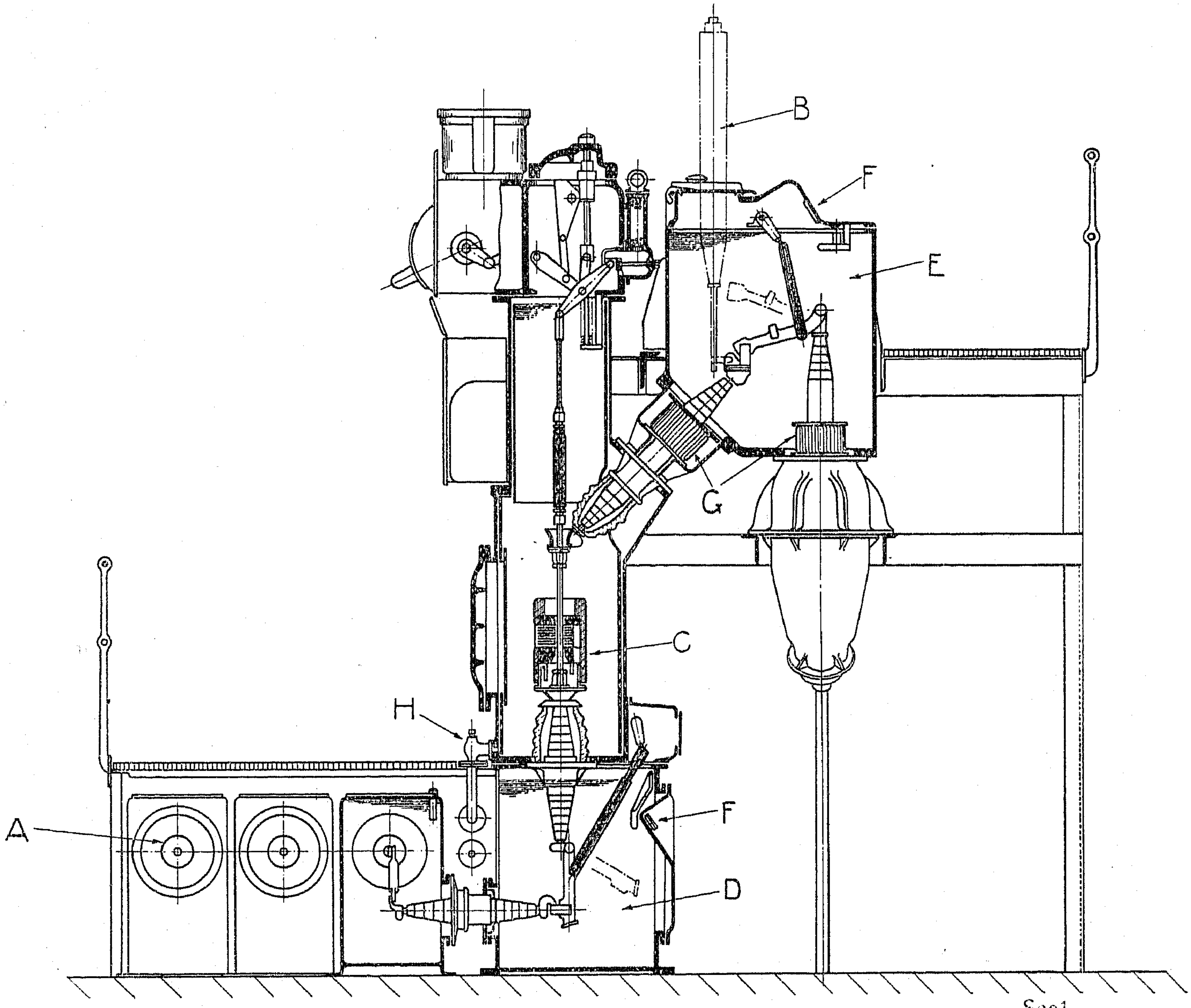


Fig. 11.—Fixed-breaker single-busbar equipment.

A = Busbars (condenser bushings).
B = Testing bushing.
C = Cross-jet explosion pot.
D = Busbar-isolating switch.
E = Cable-isolating switch.
F = Inspection window for earthed position of isolators.
G = Current transformers.
H = Oil-draining system.

At the higher voltages equivalent to those for which the breaker was designed, the percentage of duty on the one arc averaged 77 per cent measured by the peak voltages of the restriking wave, or 79 per cent measured by rate of rise of restriking voltage. Fig. 10 shows the distribution determined by voltage peaks, against arc length in inches. As the breaker opens, the capacitance between fixed and moving contacts decreases, while that between moving contact and earth increases, the distribution becoming more uneven with longer arc length.

In the particular breaker tested, the fibre jets are retained by long metal bolts, which increase the capacitance across the gaps and therefore tend to even out the duty. In higher-voltage breakers, interrupting contacts constructed of insulation in which no metal is employed become advisable (Fig. 12), and their aid is therefore lacking, while in addition the arc lengths become longer. These factors, which tend to make the distribution worse, are offset by the increased oil clearances necessary to the tank walls, and a similar order of distribution may therefore be expected on higher-voltage designs.

These tests show that the more efficient an arc interrupter is made the nearer does the voltage distribution across series gaps immediately after interruption approach the capacitance-controlled condition. The less, therefore, is the advantage to be gained from multi-break construction, unless it is of such a design as to give properly graded distribution, which is not possible with a conventional earthed-metal-tank arrangement. In extreme cases it is even possible for the voltage across one gap of a multi-gap breaker to exceed the entire restriking peak voltage across the whole breaker.

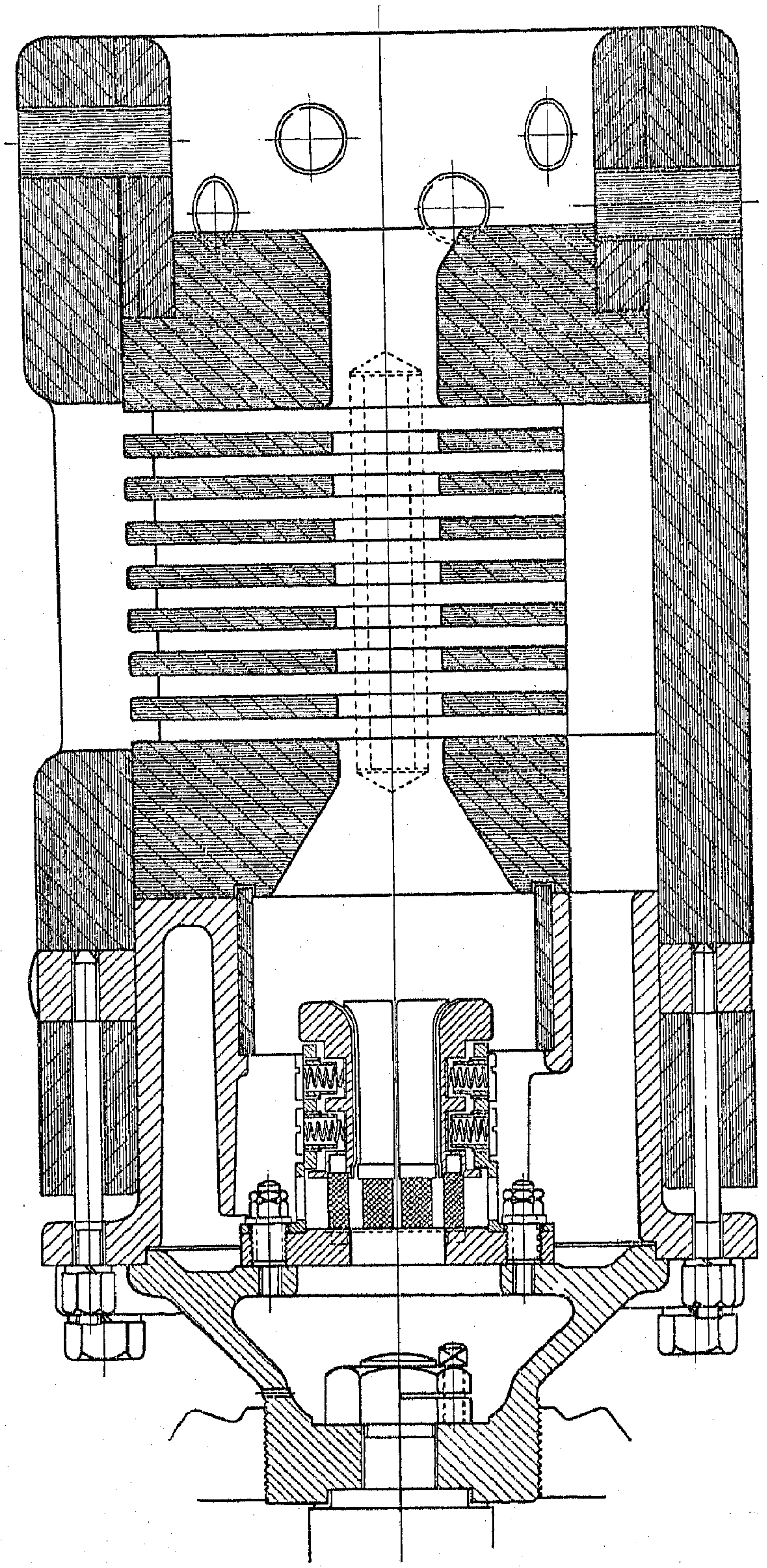


Fig. 12.—66-kV cross-jet explosion pot.

A good arc-control device giving short arc lengths must of necessity allow only negligible leakage currents to flow, and its consistent performance does not depend upon fortuitous conditions due to the action of adjacent arcs. Multiplicity of breaks with this end in view will not, therefore, be justified.

These conclusions have been borne out in practice. Increasing the number of series breaks does cut down appreciably the required mechanical stroke with many designs of plain oil breakers, although the advantage does not increase in direct proportion to the number of breaks, the total arc length being longer than that for an equivalent single-break unit. Also, arranging a number of highly efficient oil-blast contacts in series, with proper voltage grading, has been shown to increase the rating (measured by the restriking rate) in direct proportion to the number of breaks.[*] The tests given in Table 4 show that this is not so with controlled-arc type contacts arranged with the unavoidably bad static voltage distribution associated with the conventional double-break arrangement. There is shown to be only 10 per cent difference in individual arc lengths between the single and double break, although the stroke required for even one break may be less than that necessary for a multi-break plain oil circuit-breaker.

DEVELOPMENT OF THE SINGLE-BREAK METAL-CLAD UNIT

It was clear that many advantages would be obtained by the use of only one break, and, based on the above reasoning, a 66-kV single-break experimental breaker was constructed for test purposes, generally similar to one phase of the 3-phase equipment shown in Fig. 11. New features incorporated in the detail design were the sliding contact necessary with a long-stroke single-break arrangement, and an appropriate cross-jet pot.

The current is carried from the moving conductor to the fixed bushing, through a brass-to-copper spring-loaded sliding contact surface, similar to the tulip contact on the cross-jet pot itself. This has been found to carry heavy short-circuit currents without burning, scoring, or seizing, provided the correct mechanical proportions are employed, tests having been made up to 82 000 (peak) amperes and 29 400 (r.m.s.) amperes at interruption.

Although numerous tests had been made on a 66-kV double-break breaker equipped with cross-jet pots built up from fibre plates, bolted together, as has been described in an earlier paper,[†] it was considered desirable to eliminate the metal securing bolts and the risk of breakdown between these and the moving contact. The pot was re-designed on fully insulated lines (Fig. 12) in which the fibre jet assembly is held together by a wound bakelite paper tube having an internal insulating ring secured by bakelite studs. The tube itself is secured to the metal explosion chamber by high-tensile steel bolts screwed into transverse steel inserts. A rigid construction of great strength is obtained, while no metal parts extend beyond the pressure-generating chamber. The pot is arranged with 8 transverse jets, and in principle of operation is identical with the previous designs.

Short-Circuit Tests

The experimental breaker was tested for high-voltage operation at relatively low currents (test plant A) and for high currents at low voltages (test plant B). The similarity in arc lengths at different voltages permitted the probable rating of the unit to be deduced synthetically by multiplying current and voltage from different tests, and justified the production of 3-phase units for at least 750 MVA. These were built as duplicates to the experimental model except in mechanical detail and in two small changes in the explosion pot. The contact exit throat was further restricted in order to aid in shortening arcs at low currents, while the pot internal diameter was reduced slightly in order to speed up operation over the whole duty range. Single-phase and 3-phase tests were then made on two further plants (C and D). On account of the slight changes made, test-results obtained on all four plants can be considered to be comparable.

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[*] See References (6) and (7).

[†] *Ibid.*, (8).

Every test made on plants A, C, and D, has been tabulated (see Tables 5, 6, 7, and 8), and a typical selection of the heavy-current shots on plant B. Throughout the entire programme, trouble was experienced with the breaker in only two tests, as explained in the footnotes.

Fig. 13 (Plate 4) is the magnetic oscillogram of a typical make-break test (No. 13) on plant C at 600 MVA, in which a 16-element instrument is employed, recording on one film. Fig. 14 (Plate 5) is a portion of a 3-phase cathode-ray oscillogram for test No. 5 on plant C, and is analysed in the Appendix. Fig. 15 (Plate 6) is an oscillogram of a typical 3-phase test at over 1 000 000 kVA on plant D. The similarity in arc durations and lengths, independent of voltage, is shown in Figs. 16 and 17, in which every single- or 3-phase test made on the 66-kV single-break unit has been plotted. For purposes of comparison with single-phase tests, the first phase to clear of 3-phase tests has been selected, associated with 86·6 per cent or

Table 5

TESTS MADE ON SINGLE-POLE SB24 ON TEST PLANT A

Test No.	Duty	Test voltage	Recovery voltage	R.M.S. current (initial) in arc	Single-phase MVA interrupted on recovery voltage	Arc duration (½-cycles)	Arc length
		kV	kV	amps.	MVA		in.
1	B	42·6	42	33	1·35	7·0	8·5
2	MB	44·5	44	33	1·45	6·5	7·5
3	B	55	54	73	3·9	7·0	9·5
4	MB	55	53·5	72·5	3·9	9·5	11·5
5	B	65·5	60	261	15·8	6·5	8·5
6	MB	66	60	258	15·5	6·5	6·5
7	B	66	59·5	1 590	95	4·5	6·0
8	MB	67·5	55·6	1 390	77·5	7·0	7·5
9	B	66	62	1 730	107	5·0	6·5
10	B	65·5	61	1 670	101·5	5·25	7·5
11	B	16	14	7 500	105	4·0	6·5
12	B	16	13·2	7 500	99	16·5	17·0*
(New pot with original jets fitted.)							
13	B	64	62·5	58	36	27·5	17·0†
14	B	65	63	89	56	6·0	8·5
15	MB	65	63·5	87·5	55·5	9·0	10·0
16	B	54·5	53·6	44	23·6	7·5	10·5
17	MB	54·6	53·5	44	23·5	8·75	10·0
18	B	32·6	28·6	4 060	116	5·25	7·0
19	B	32·2	28	3 700	104	5·0	7·5
20	MB	13·8	11·6	2 320	27	6·0	7·5
21	MB	17·6	14·4	3 100	44·5	5·25	6·5
22	MB	10·8	9·6	3 540	34	5·0	6·0
23	MB	10·8	9·2	4 400	40·5	5·0	6·5
24	B	14·5	12·8	8 750	112	4·5	7·5
25	B	14·8	13·2	7 200	95	4·1	5·5
26	B	15·0	13·3	6 600	87·5	3·6	5·5
27	B	15·5	13·7	8 050	111	3·7	6·0

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* Although the breaker cleared, the cross-jet pot burst on this test and was rebuilt with a considerably stronger tube, since when no fracture has occurred on any test.

† In the test at 64 kV the breaker arced to the end of the stroke before interrupting. This actual condition could not arise in 66-kV service, since even with a 3-phase fault the highest voltage across one phase would not exceed 57 000 volts. More important, however, is the fact that such small currents could not occur in an actual system at the low lagging power factors at which these tests were made. They would be either load currents at approximately unity power factor, or charging currents at approximately zero leading power factor.

Load current is very easy to clear, since the restriking voltage appearing across the contacts only rises along a 50-cycle wave, instead of along a high-frequency oscillation at the system natural oscillating frequency.

Charging currents are also easy to clear initially, since the rate of build-up of voltage is again very low. Difficulty only occurs when repeated subsequent breakdown [see Reference (9)] causes high voltages to be built up. Tests have shown that this phenomenon does not occur on breakers equipped with cross jets.

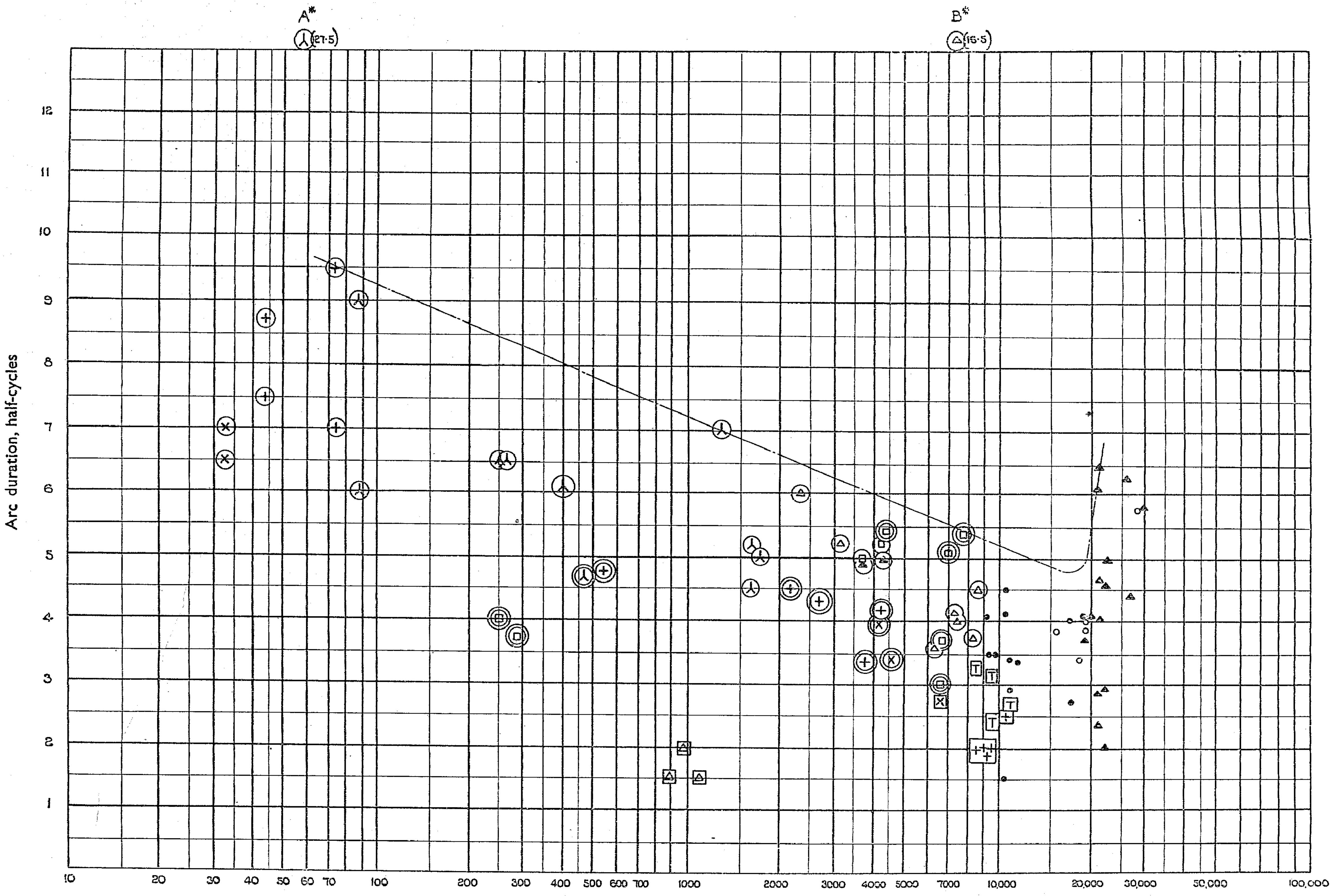


Fig. 16.—Summary of short-circuit tests made on 66-kV single-break oil circuit-breakers.

Key to symbols referring to Recovery Voltage (Single Phase)

⊕ 3 000–5 000. ○ 5 001–7 000. ▲ 7 001–10 000. △ 10 001–15 000. ▨ 15 001–25 000. □ 25 001–35 000. × 35 001–45 000. + 45 001–55 000. ⅄ 55 001–65 000. T 65 001–75 000.

Key to symbols referring to Test Plants.

X Tests on plant B. ⊗ Tests on plant A. ⊗ Tests on plant C. ☒ Tests on plant D.

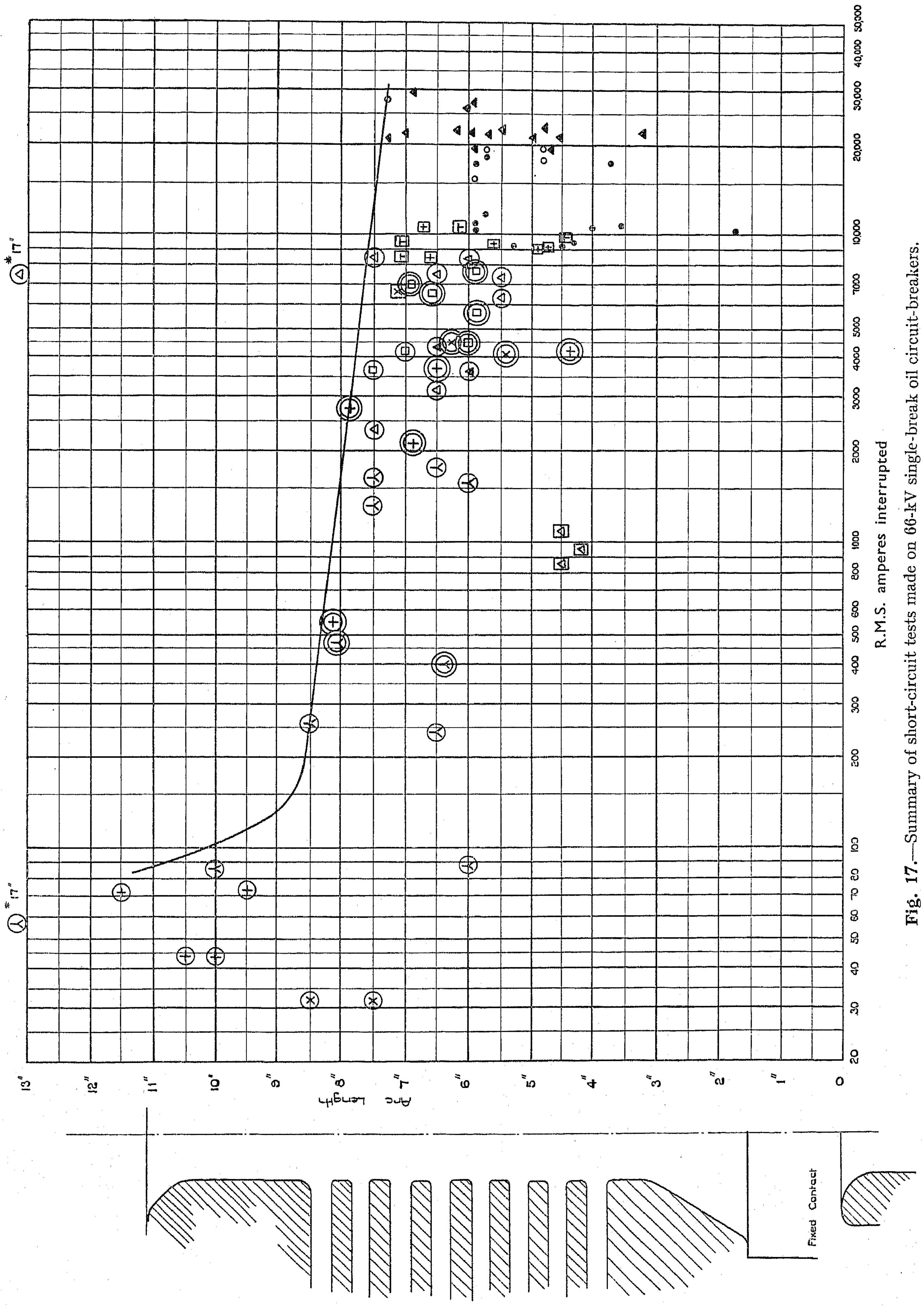


Fig. 17.—Summary of short-circuit tests made on 66-kV single-break oil circuit-breakers.

57 per cent line recovery voltage as determined by the system earthing connections.

Table 6

TYPICAL TESTS MADE ON SINGLE-POLE SB24 ON TEST PLANT B

Test No.	Duty	Test voltage	Recovery voltage	R.M.S. current (initial) in arc	Single-phase MVA interrupted on recovery voltage	Arc duration (½-cycles)	Arc length
		kV	kV	amps.	MVA		in.
1	B	4·8	3·23	11 500	37·2	2·9	4·0
2	MB	5·07	3·23	11 250	36·4	3·4	3·6
5	B	6·2	4·2	10 200	43·0	4·2	5·9
6	MB	6·4	3·9	10 300	40·6	4·5	5·9
14	B	8·6	5·8	15 200	89	3·8	5·9
15	B	9·2	7·2	19 400	141	3·7	5·9
16	MB	9·2	6·7	28 400	190	5·7	7·3
17	B	9·7	7·6	22 400	171	4·0	5·7
31	MB	9·6	7·8	21 200	173	6·5	7·0
32	MB	9·3	7·5	25 600	193	6·3	6·0

Table 7

3-PHASE TESTS ON SB24 ON TEST PLANT C

Test No.	Duty	Phase-to-phase test voltage	Phase-to-phase recovery voltage	R.M.S. current (initial) in arc (average)	3-phase MVA interrupted on recovery voltage	Breaker operating time (cycles)	Arc duration (½-cycles)	Arc length	Rate of rise of restriking voltage	
									Actual voltage per microsec.	Inherent
		kV	kV	amps.	MVA	cycles		in.		
T7	B	34·2	33·8	250	14·5	5·7	5	8·9		
1	B	64·2	63	500	54·4	5·7	5	9·2	950	920
2	B	64·2	59·5	3 200	328	5·2	3·8	8·0		
3	MB	61·5	53	2 240	205	6·3	4·9	8·3		
4	MB	62·8	57	3 840	379	5·7	4·7	5·7		
5	MB	64·2	51·5	4 530	403	5·6	4·0	5·9	2 130	2 560
6	MB	61·5	51	4 400	387	5·85	4·6	7·4		
(New contacts and cross-jet pots fitted)										
T11	B	32·9	32·9	286	16·3	5·15	4·2	7·2		
7	B	67·2	66	510	58·8	5·6	5·2	10·0		
8	MB	67·2	66	420	47·4	6·0	6·8	8·7		
9	B	66·6	59·3	3 150	323	5·45	4·8	9·7		
10	B	66·6	57·5	5 150	513	5·1	4·2	8·1		
11	MB	67·2	53·4	4 400	407	5·1	6·2	7·5		
12	B	68·4	54·2	6 310	592	5·5	4·7	8·5	2 620	3 250
13	MB	67·2	54·2	6 350	600	5·4	6·8	8·6		
14	MB	70·8	54·2	7 420	694	5·1	5·6	7·8		

All tests with switch star-point earthed.
Tests Nos. 1–9—Transformer neutral insulated.
Tests Nos. 10–14—Transformer neutral earthed.

Three-phase tests have been conducted up to 1 029 MVA at 59 kV recovery voltage, and single-phase tests have also been made up to 760 MVA at 70·8 kV recovery voltage, directly equivalent to 1 520 MVA at 82 kV (3-phase). With similar arc lengths, the contact has withstood the pressures generated by currents of 2½ times that in the above test, corresponding to a figure of nearly 4 000 MVA, obtained synthetically by multiplication of maximum currents and voltages from the separate tests.

While a reasonable factor of safety, varying with the consistency of operation of the breaker, must be allowed in the rating of breakers from synthetic tests, such a figure is of value in demonstrating that a margin exists, and the method is in fact the only one available of proving the larger breakers on existing test plants.

equipment. Commencing at about 22 kV, and upwards, the oil clearances required for insulation purposes demand relatively larger tanks with multi-break construction, in consequence of which a reduction in breaker size is made possible by the small tank diameters associated with single-break design. This is illustrated in Fig. 18, which shows to scale the plan views of a double-break 66-kV round-tank breaker, a double-break 66-kV oval-tank unit designed to reduce the phase centres but requiring very heavy construction in order to maintain the desired strength, and a 66-kV single-break round-tank unit.

Table 8

TESTS MADE ON SB24 ON TEST PLANT D

Three-Phase Tests

Test No.	Duty	Phase-to-phase test voltage	Phase-to-phase recovery voltage	R.M.S. current (initial) in arc (average)	3-phase MVA interrupted on recovery voltage	Breaker operating time (cycles)	Arc duration (½-cycles)	Arc length
		kV	kV	amps.	MVA			in.
4411	B	17	13·5	1 050	23·4	—	1·5	4·5
4411	MB	17	12·3	880	18·8	—	1·5	4·5
4412	B	66	57·5	8 500	877	7·1 *	3·0	6·6
	3 minutes							
4412	MB	66	50·2	6 800	577	7·25	3·1	6·9
4413	B	12·1	12·1	970	20·5	4·9	2·0	4·2
4414	B	66	57·8	10 400	1 019	5·8	3·0	6·6
4415	B	66	58·9	9 500	1 026	5·6	2·3	5·6
	3 minutes							
4415	B	66	60·2	9 000	993	5·3	2·18	4·7
	3 minutes							
4415	B	66	60·2	9 150	983	5·3	2·33	4·75

* Trip coil under-excited in these tests.

Single-Phase Tests on New Contact and Pot Assembly

		Single-phase	Single-phase		Single-phase MVA interrupted on recovery voltage	Breaker operating time (cycles)	Arc duration (½-cycles)	Arc length
					MVA			in.
4416	B	76	69·5	9 700	695	5·25	2·37	4·4
	3 minutes							
4416	B	76	68	8 350	564	6·30	3·25	7·0
4417	B	76	70·8	10 800	760	5·50	2·64	6·2
	2 minutes							
4417	B	76	—	9 550	—	6·40	3·0	7·0†

† External flashover between temporary test bushings and earth short-circuited the breaker on this test.

All tests with transformer neutral earthed. Switch star-point insulated.

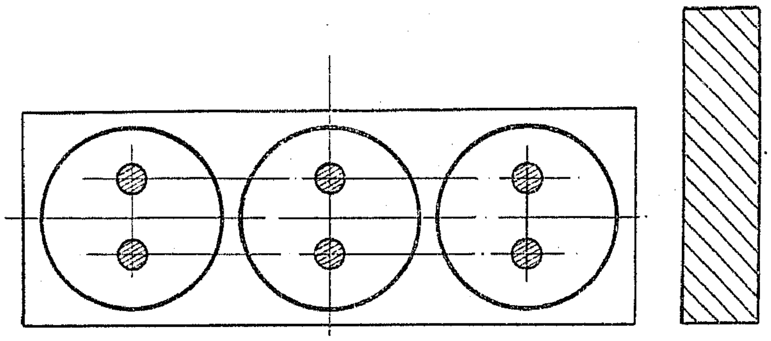
COMPARISON OF COMPLETE SINGLE-BREAK AND DOUBLE-BREAK METALCLAD EQUIPMENTS

It has been shown that with an efficient arc-control device one break gives consistent and reliable operation; while if two or more breaks are used, with normal metalclad design, each will need to be equally long, and the total arc length and consequently oil deterioration will be increased almost in proportion to the number of breaks. Mechanically, however, single-break construction is not so well adaptable to low-voltage as to high-voltage breakers, as it is difficult to produce a design simpler than the conventional double-break 11-kV

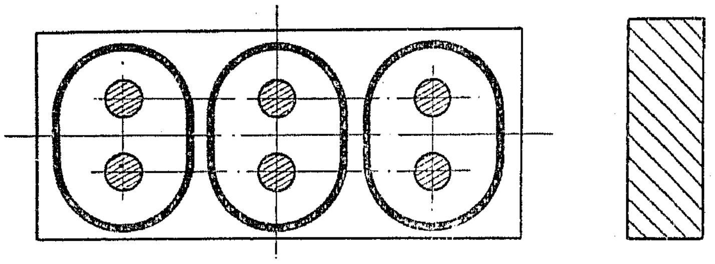
Fixed Breaker, Single-Busbar Equipments

The reliability of the modern controlled-arc breaker has reduced the necessity for removable circuit breakers, and unit construction of breaker, isolators, and busbars, has become a practicable proposition. The single-break design lends itself very readily to this form, and Fig. 11 shows such an arrangement for a 66-kV single-busbar system which has been in service since September, 1934. Isolation is effected by means of oil-immersed ganged blades, interlocked with the breaker and controlled from the operating passageway by hand-wheels. They have running, isolated, and earthed positions, in the last of which the blades themselves are visible through oiltight windows in the isolating chambers.

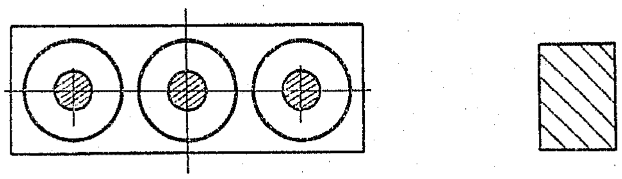
The busbars are constructed in the form of condenser bushings having sheet-metal earth bands reinforced by banding wire soldered on. Provision for longitudinal expansion and contraction is made at one end of each bar by means of a stuffing-gland joint at the entry into the isolator chambers, the bearing surface of the bar at this point being a brass sleeve shrunk on to the paper of the bushing. The usual flexible bellows are thereby eliminated. Further provision is made for slip between the conductor and paper winding, the arrangement being such that adhesion between paper and conductor is provided for a few feet at one end only, sufficient to prevent oil seepage along the joint. Deterioration by the tearing action which would otherwise follow on the unequal longitudinal expansion of rod and insulation is thereby obviated. Satisfactory service of a large number of condenser bars has proved the soundness of this design.



Round-tank plain double-break



Oval-tank cross-jet double-break



Round-tank cross-jet single-break

Relative oil volume in tanks

Fig. 18.—Comparison of single- and double-break 66-kV oil circuit-breakers.

The ends of bushings entering the interrupting tank are protected by porcelain insulators from hot gases and creepage discharge due to carbon deposit, the annular oiltight spaces formed being pre-filled with clean oil. The cable-sealing end is inclined in order to reduce the headroom required and to permit a large radius for the cable bends.

Fixed Breaker, Duplicate Busbar Equipments

Fig. 19 shows a duplicate busbar arrangement for voltages up to 132 kV, the feeder switches being arranged in a row and the three phases for each breaker being in a column. The breakers therefore run in a line at right angles to the centre line of the three phases of one feeder. Each single-break switch is mounted over the corresponding phase of duplicate busbars, being separated from these by a fireproof floor, while the busbar and its duplicate are again separated from one another, each being in its own tunnel. The cables for one feeder pass along the chamber which accommodates the three single-break switches, through a fireproof partition at the end into one of several tunnels accommodating feeder cables only. The control cables pass along a separate duct parallel to the main feeder. Independent mechanisms are shown on each phase in the interests of extra-high-speed operation.

Fig. 20 shows a 33-kV fixed-breaker duplicate-busbar design. Both this equipment and that in Fig. 19 are suitable for either indoor or outdoor mounting.

Removable Breaker Equipments

Although fixed designs are adequate for most installations, and are considered advisable for outdoor gear, for large generating stations the increased flexibility of operation and maintenance afforded by removable breakers may justify the additional cost, while station designers have recently in several instances specified two removable breakers per circuit. It is recognized that isolation at 66 kV and over is best effected under oil, and for this reason vertical lift-up gear is to be preferred to horizontal or drop-down air-isolated withdrawal arrangements, since oil-immersed plugs and sockets can be employed. Fig. 21 shows a duplicate-busbar single-break arrangement of this type.

Maintenance

Maintenance is facilitated by the accessibility of the contacts, which can be inspected and withdrawn through the hinged swing door without the usual necessity for lowering tanks, while the parts to be maintained are halved in number as compared with the conventional units. The bushing-type current transformers can also be removed with the minimum of disturbance to other parts of the gear.

Provision for cable testing is made by three portable bushings, which can be inserted through the opening in the top of the feeder isolator chamber, as indicated in Figs. 19 and 20. The isolator blades are then rotated into contact with the bushings, thus permitting test voltage to be applied to the cables, while two cores may be earthed if desired.

Apart from the advantages gained by single-break design, the fixed-tank arrangement also lends itself to easy oil handling, by means of a permanent pipe and valve system.

Plate 1

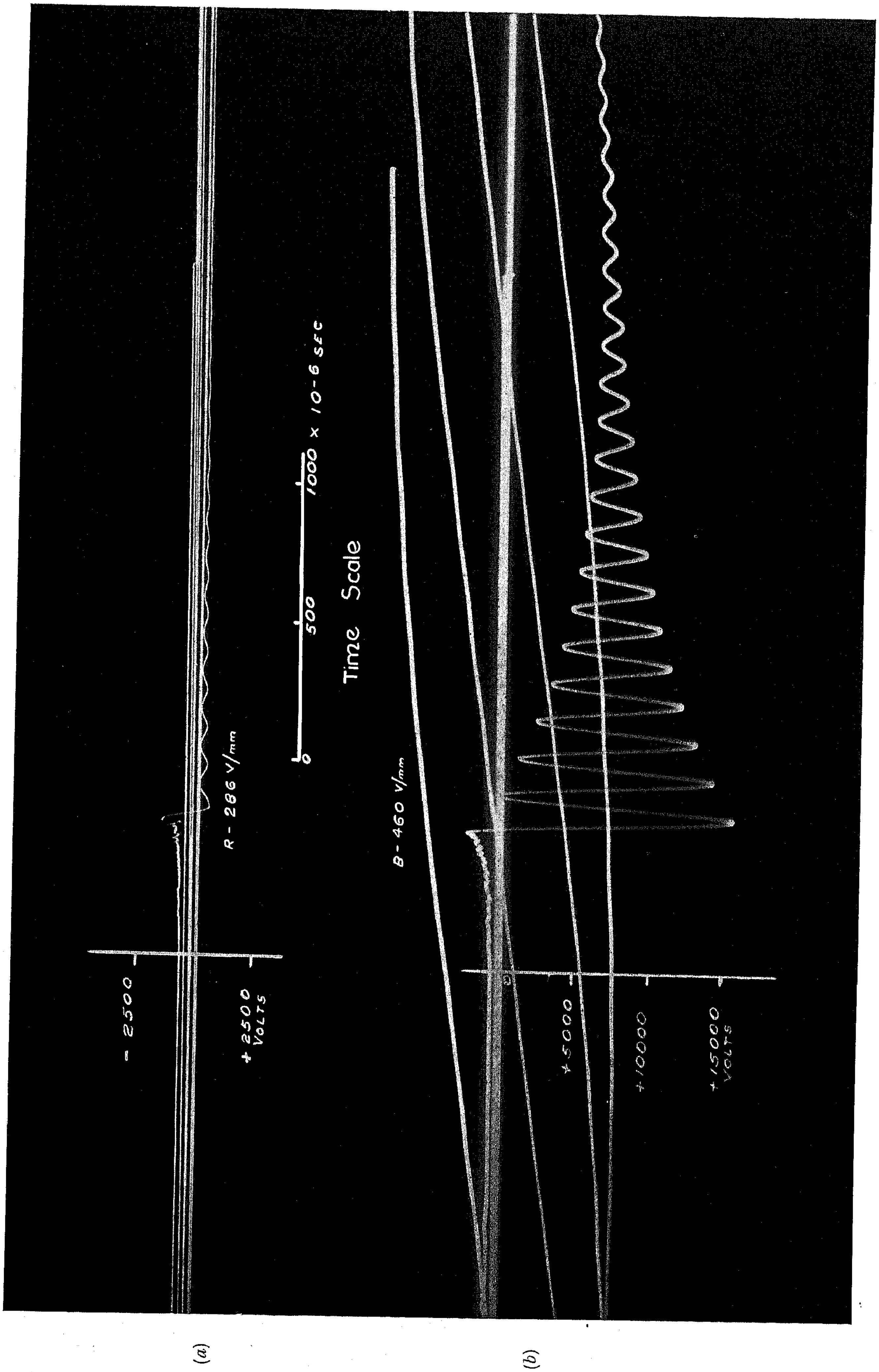


Fig. 4.—Cathode-ray oscillogram of cross-jet breaker operation (test No. 2).

(*a*) Voltage across earth side of breaker (V_B).
(*b*) Voltage across entire breaker ($V_A + V_B$).

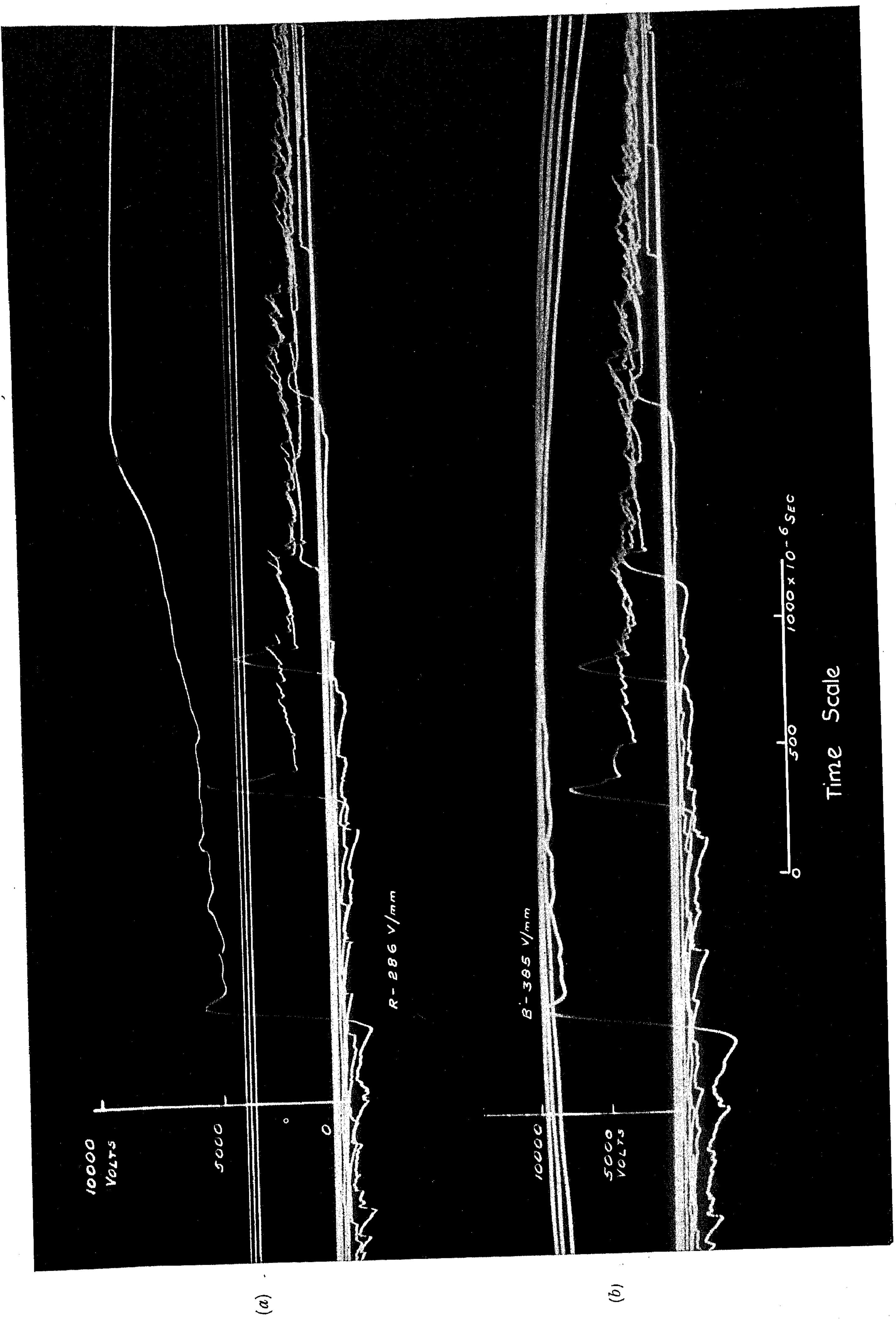


Fig. 5.—Cathode-ray oscillogram of plain-break operation (test No. 4).

(*a*) Voltage across earth side of breaker (V_B).
(*b*) Voltage across entire breaker ($V_A + V_B$).

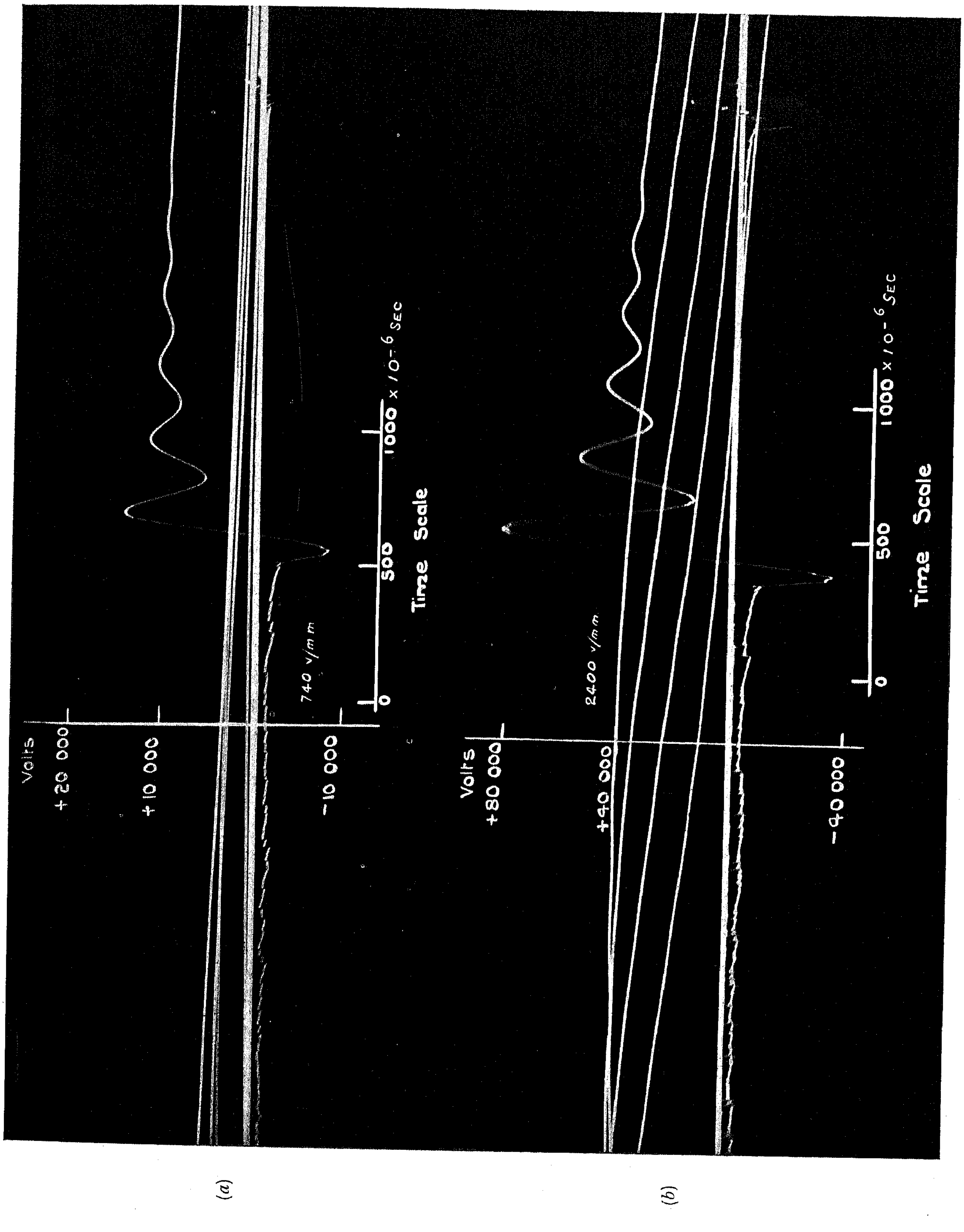


Fig. 9.—Cathode-ray oscillogram of cross-jet breaker operation (test No. 13).

(*a*) Voltage across earth side of breaker (V_B).
(*b*) Voltage across entire breaker ($V_A + V_B$).

Plate 4

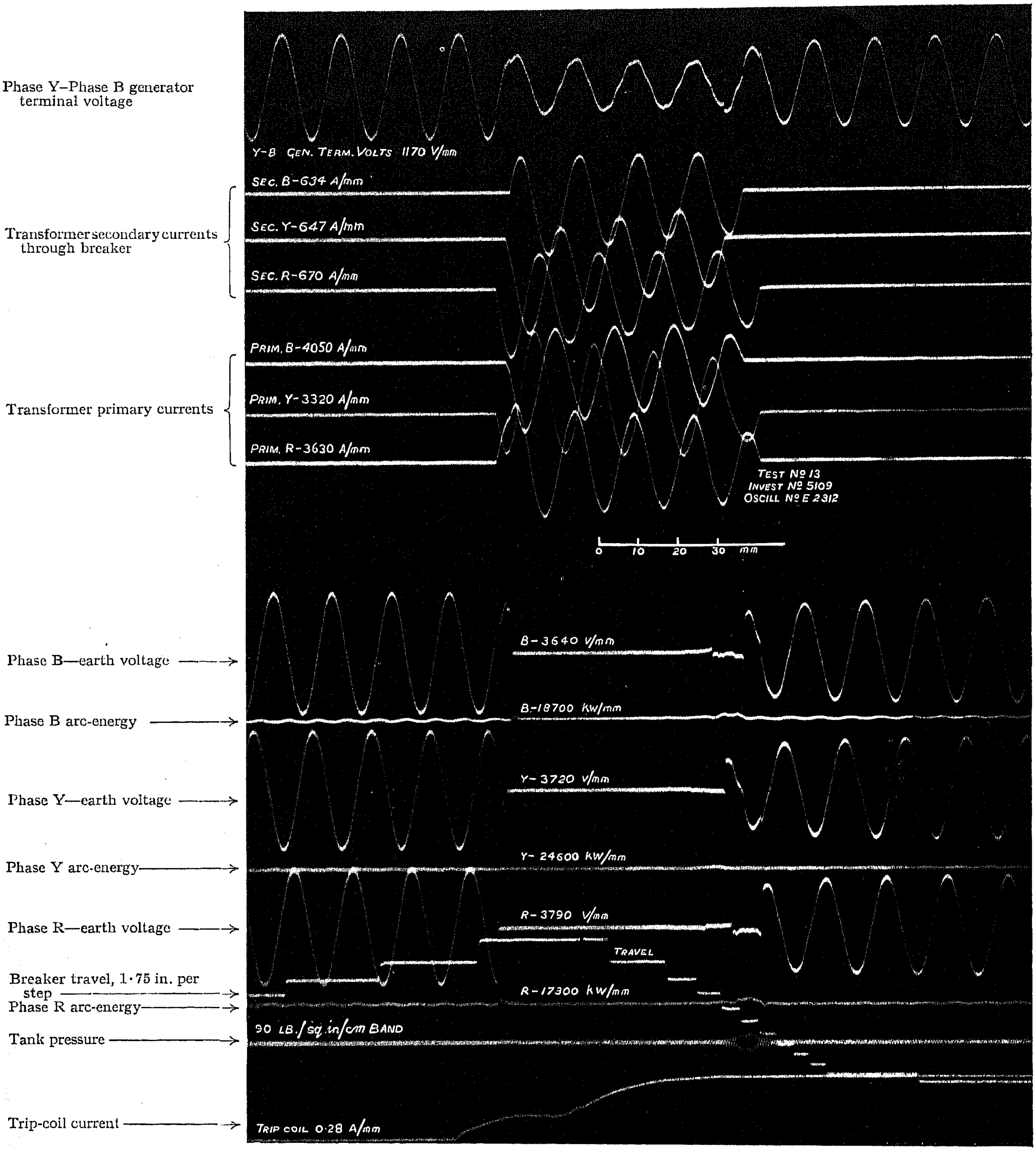


Fig. 13.—Magnetic oscillogram of " make-break " short-circuit test at 600 000 kVA.

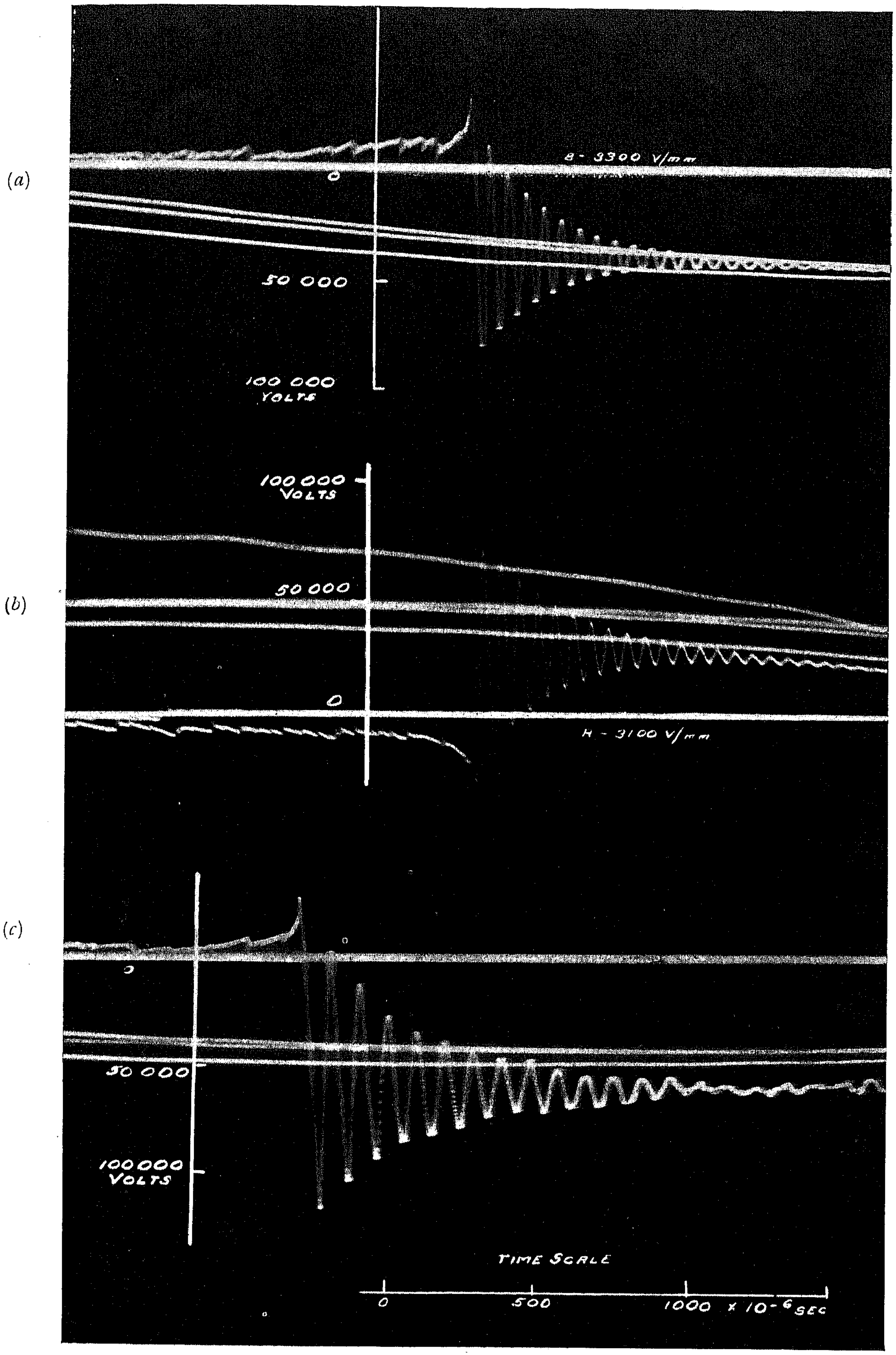


Fig. 14.—Cathode-ray oscillogram of 3-phase short-circuit.

(*a*) and (*b*) Voltage across blue and red phases, clearing simultaneously ¼ cycle after yellow phase.
(*c*) Voltage across yellow phase, the first to interrupt.

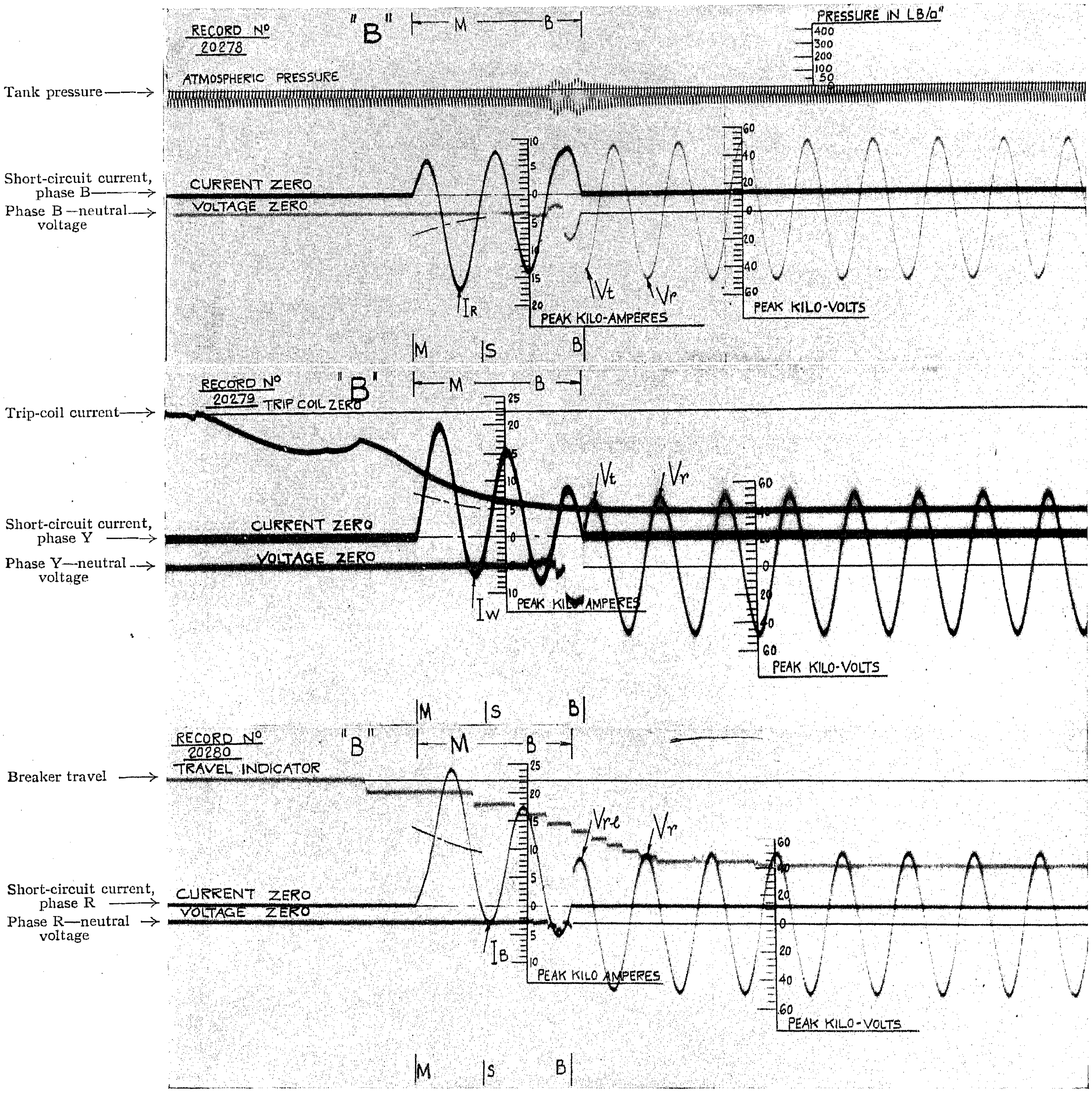


Fig. 15.—Magnetic oscillogram of " break " short-circuit test at 1 029 000 kVA.

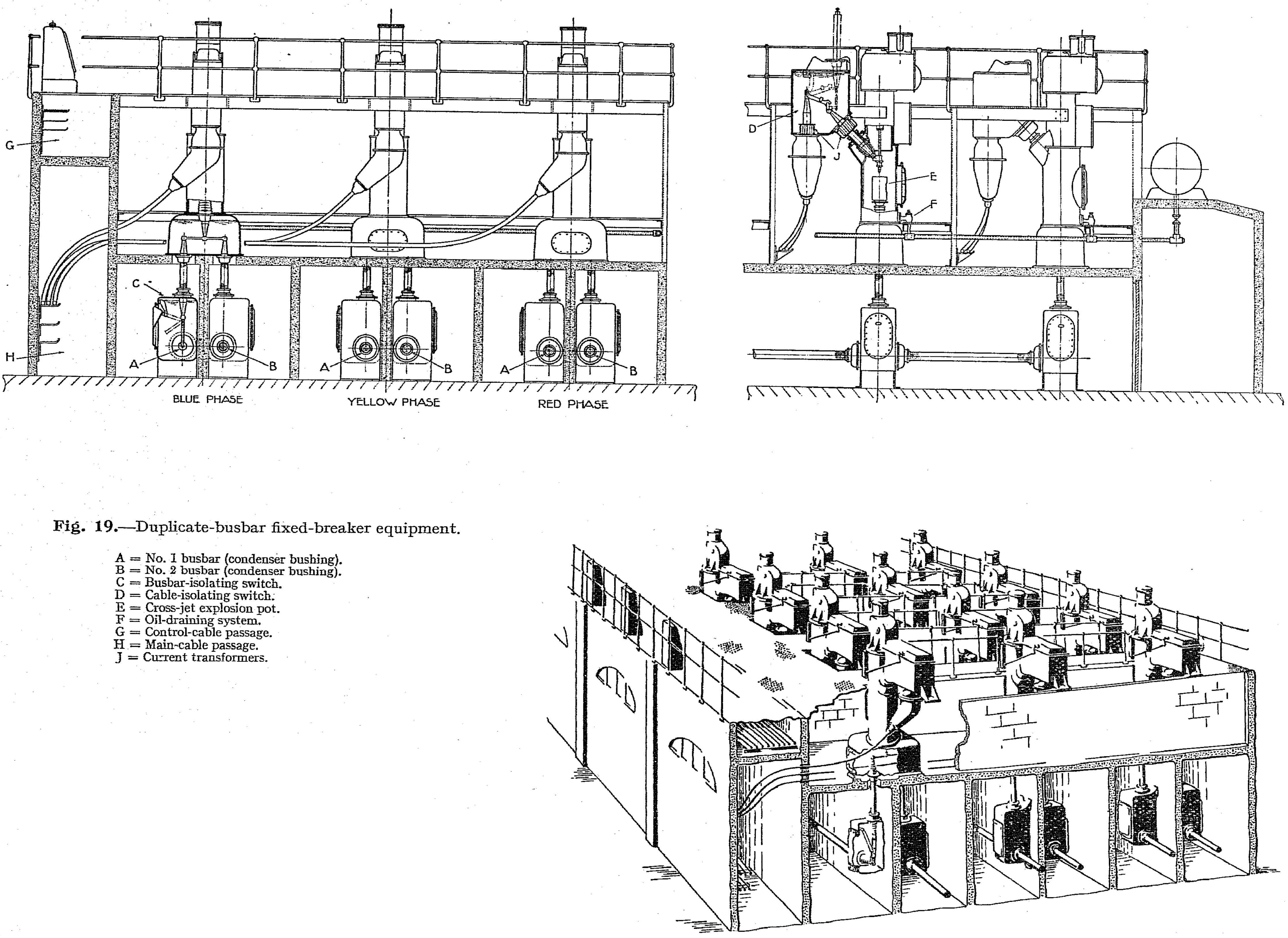


Fig. 19.—Duplicate-busbar fixed-breaker equipment.

A = No. 1 busbar (condenser bushing).
B = No. 2 busbar (condenser bushing).
C = Busbar-isolating switch.
D = Cable-isolating switch.
E = Cross-jet explosion pot.
F = Oil-draining system.
G = Control-cable passage.
H = Main-cable passage.
J = Current transformers.

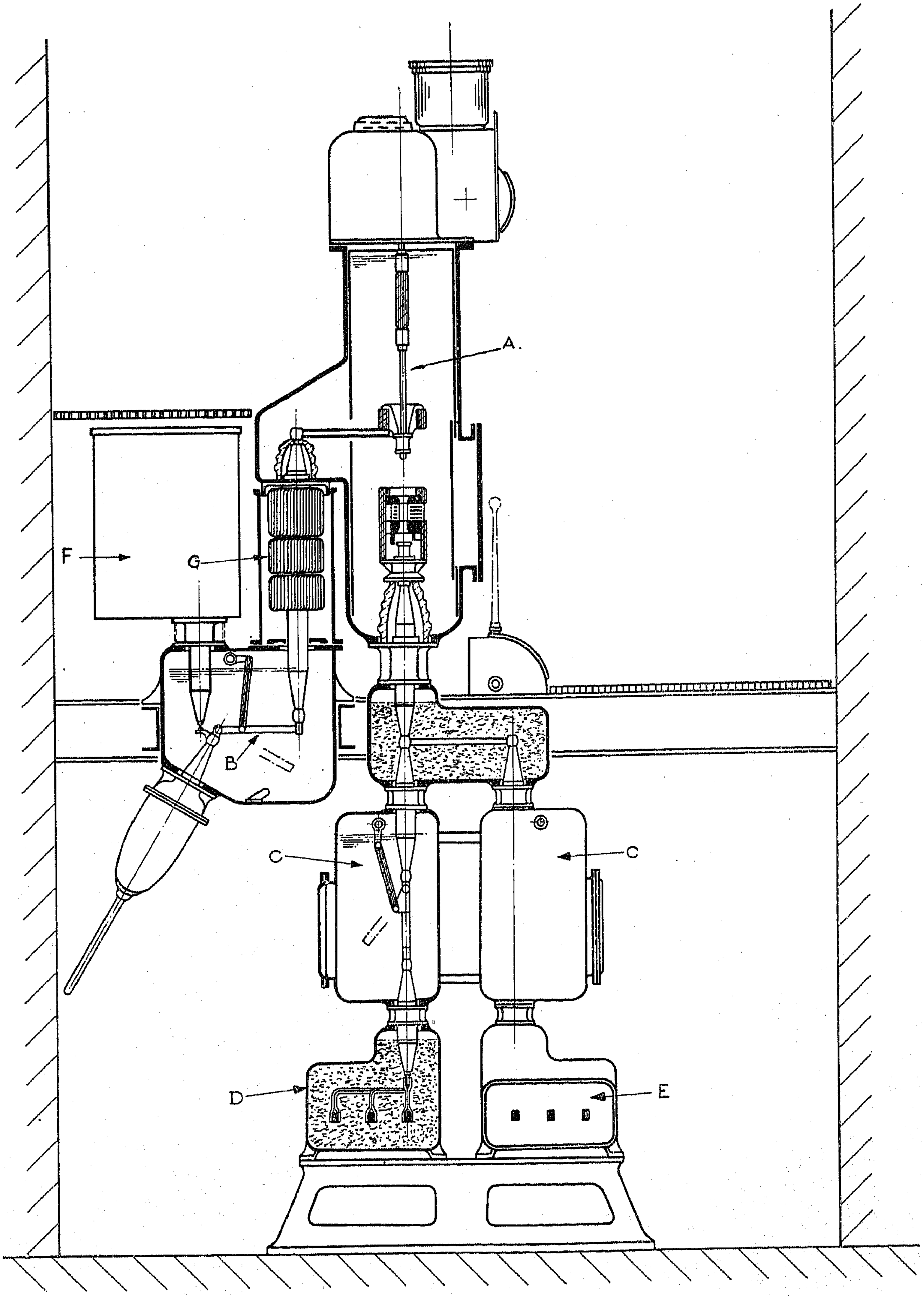
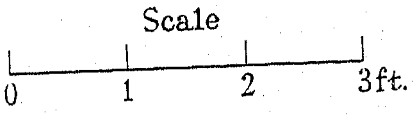


Fig. 20.—33-kV fixed-breaker duplicate-busbar equipment.

A = Fixed circuit breaker.
B = Feeder isolator.
C = Busbar isolators.
D = No. 1 busbars.
E = No. 2 busbars.
F = Voltage transformer.
G = Current transformer.



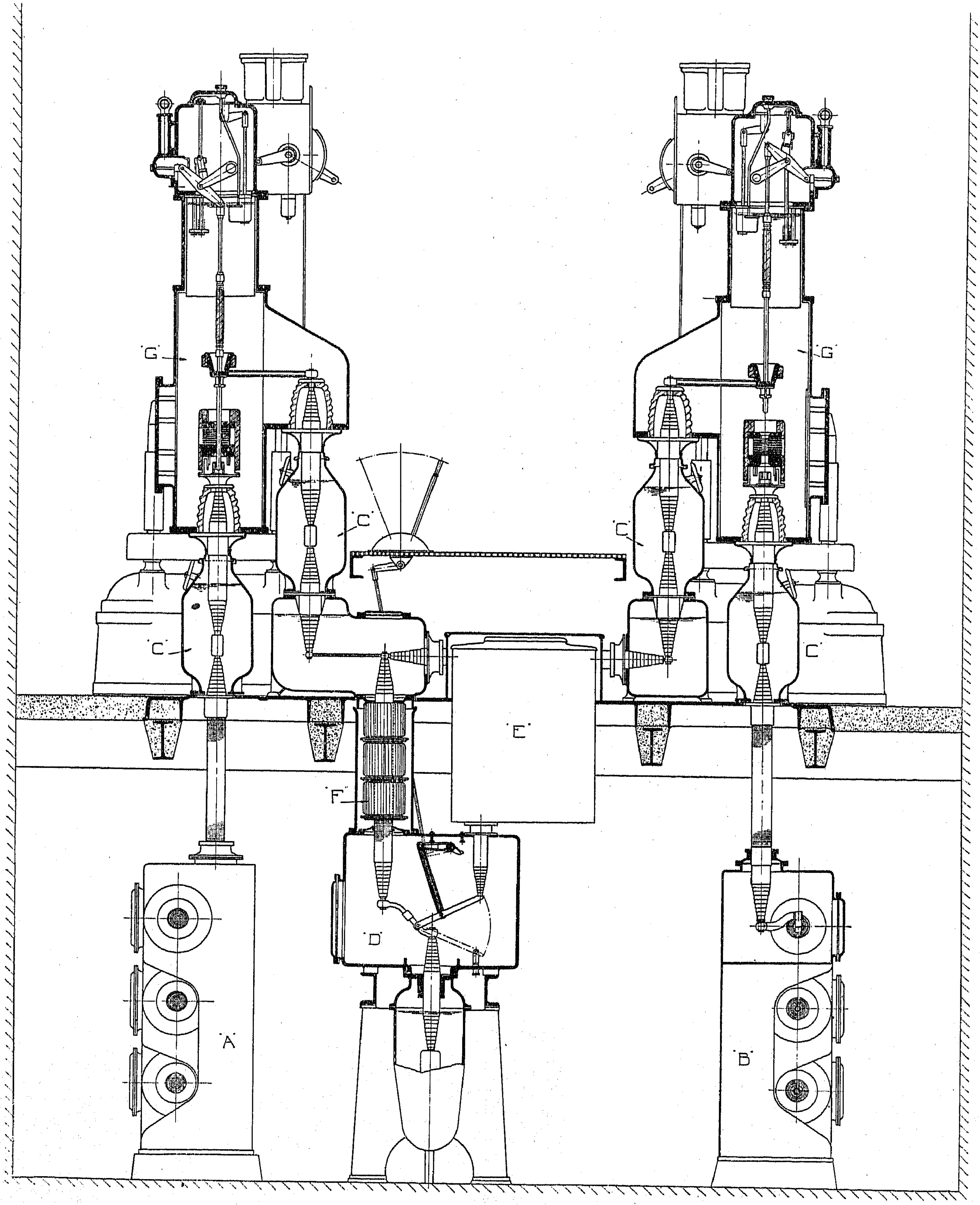


Fig. 21.—Duplicate-busbar removable circuit-breaker equipment.

A = No. 1 busbar (condenser bushing).
B = No. 2 busbar (condenser bushing).
C = Oil-immersed plug spouts and shutters.
D = Cable-earthing switch.
E = Voltage transformer.
F = Current transformers.
G = Removable lift-up oil circuit-breaker.

CONCLUSION

The single-break metalclad high-voltage breaker with arc-control contacts enables a reduction to be made in weight, space occupied, oil volume, and in overall installed costs for complete high-voltage equipments, while at the same time it facilitates and reduces the maintenance work required. It provides an interrupting capacity equal to that of the multi-break construction, and faster overall operating times can be obtained, owing to the reduction in accelerating forces required. If necessary, an operating time of 5 cycles from the receipt of tripping impulse to interruption, on a 66-kV system, can be obtained with special flux-diverting magnetic latching devices, with a consequent increase in system stability under fault conditions.

It is expected that the single-break metalclad construction will be extended to higher voltages as the demand for this class of gear arises, no difficulties being anticipated at any working voltage employed in this country.

ACKNOWLEDGMENTS

The authors wish to thank the testing staffs of the Allgemeine Elektricitäts Gesellschaft, Berlin, the British Short Circuit Testing Co., Metropolitan-Vickers Electrical Co., Ltd., and the Switchgear Testing Co., for their assistance in carrying out the short-circuit tests. In particular they wish to acknowledge their indebtedness to Messrs. A. C. Ehrenberg and R. A. Polson, who operated the cathode-ray equipment, and to Mr. A. K. Nuttall for advice in connection with the capacitance-divider design. The authors have also to thank the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish this paper.

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APPENDIX I

Analysis of Restriking-Voltage Phenomena

Three-phase cathode-ray oscillograms were taken in tests Nos. 1, 5, and 12, test plant C, with a rotating-drum type oscillograph. That for test No. 5 is reproduced in Fig. 14 (Plate 5), in which only the actual restriking oscillations are shown, the complete film being 36 in. long. The method of analysis is given below.

Test No. 5.

For the first phase to clear, at the instant of interruption, the r.m.s. value of recovery voltage as given by the phase-to-phase record is 74 per cent of the rated service voltage of the breaker. The theoretical instantaneous recovery voltage appearing across the first phase in this test, with insulated neutral and earthed fault, is therefore

$$66\,000 \times 0{\cdot}74 \times 0{\cdot}866\sqrt{2} = 60\,000 \text{ volts}$$

The value given by the cathode-ray oscillograph calibration is 59 300 volts.

The restriking oscillation comprises two frequencies differing by only 6 per cent, and equivalent to one at 10 700 cycles per sec. The inherent rate of rise of this circuit is measured by the maximum average slope as given by the tangent to the first oscillation, drawn through the point on the zero-voltage axis at the time of current interruption, and is therefore

$$N_1 = 10\,700 \times 4{\cdot}55 \times 59\,300 \times 10^{-6}$$
$$= 2\,870 \text{ volts per microsec.}$$

as shown in Fig. 22(*a*).

Owing to circuit resistance, a logarithmic damping is introduced and the true inherent rate is reduced to

$$N_2 = 2\,870 \times \text{damping factor } (0{\cdot}91)$$
$$= 2\,620 \text{ volts per microsec.}$$

In the actual test, this rate has been modified by various phenomena as is shown in Fig. 22(*b*), where it is represented by

$$N_3 = 2\,130 \text{ volts per microsec.}$$

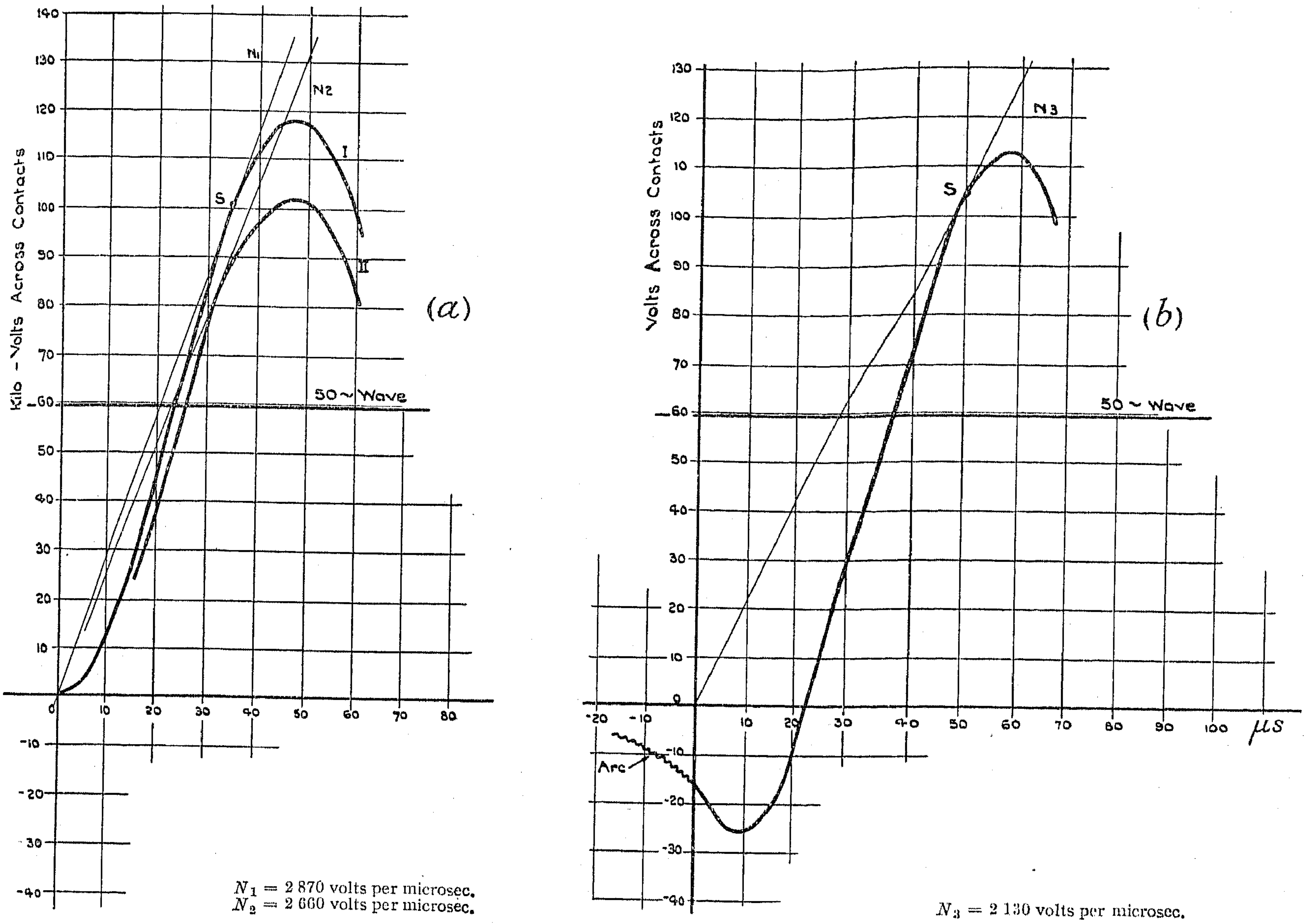
The effective value of the fundamental about which the restriking wave oscillates has been reduced 2 per cent by the circuit phase angle differing from 90°, which reduction is chiefly due to power factor, the wave being almost exactly symmetrical.

In addition, the fundamental has a sub-transient rise of 12 per cent during the first 100 microsec., and, since the theoretical values do not allow for this phenomena, the amplitude of the first peak restriking wave is reduced below the calculated value in this instance by 7 per cent.

The arc voltage has caused an increase in amplitude which has been further augmented by the reverse wave due to current "cut off" prior to the true zero, at a value of 6 amperes. The slope of the tangent has, however, been reduced owing to the additional time introduced by the reverse wave more than counterbalancing the increase in amplitude.

Subsequent Phases to Clear (B and R).

In these cases the calculated instantaneous 50-cycle recovery voltage appearing across each phase is:—



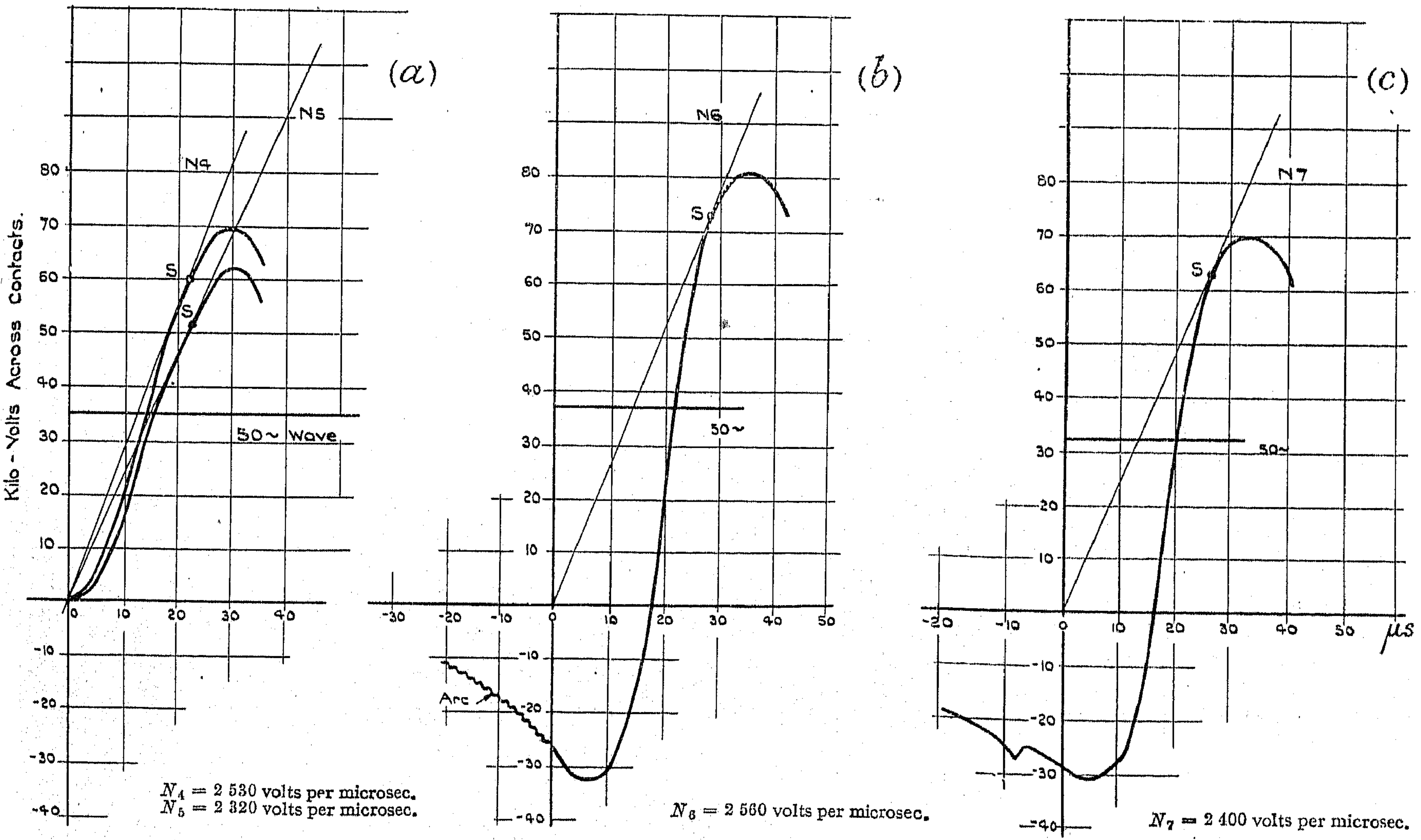
N_1 = 2 870 volts per microsec.
N_2 = 2 660 volts per microsec.

N_3 = 2 130 volts per microsec.

Fig. 22.—Analysis of first phase to clear.

(*a*) Inherent restriking waves.

(*b*) Actual restriking wave.



N_4 = 2 530 volts per microsec.
N_5 = 2 320 volts per microsec.

N_6 = 2 560 volts per microsec.

N_7 = 2 400 volts per microsec.

Fig. 23.—Analysis of last phases to clear of film shown in Fig. 14.

(*a*) Inherent waves.

(*b*) Actual restriking wave, phase B.

(*c*) Actual restriking wave, phase R.

$$\frac{66\,000}{\sqrt{3}} \times 0{\cdot}74 \times \sqrt{2} \times (\text{phase factor of } 0{\cdot}866) = 34\,800 \text{ volts}$$

The phase factor is due to the final current zero occurring 90° after the first phase clears, at a time when the phase voltages are only $0{\cdot}866 \times$ maximum.

The main frequency in this case is 16 900 and the undamped inherent rate is

$$N_4 = 4{\cdot}55 \times 34\,800 \times 16\,900 \times 10^{-6} = 2\,530 \text{ volts per microsec.}$$

giving a damped rate of

$$N_5 = 2\,320 \text{ volts per microsec. (Fig. 23).}$$

Owing to the change in vector relationships produced by power factor and asymmetry, the total voltages appearing across the two final phases to clear need not actually be as great as the phase-to-phase peak, nor need this final zero occur 90° after the first phase clears. Normally, the total voltage, with insulated neutral and earthed fault, will be distributed equally between the phases, with the neutral oscillating, but if any asymmetry in the electrical system exists, out-of-balance may result, and in this instance the voltages occurring are 36 500 (phase B) and 32 500 (phase R). The remaining modifying factors occur as in the former case, except that their net effect in this instance has been to raise the observed rate above the inherent to a value of

$$N_6 = 2\,560, \text{ and } N_7 = 2\,400, \text{ volts per microsec.}$$

Table 9 summarizes the data for three tests, and it will be seen that in all cases the current was cut off before the true zero, showing that no leakage current flowed during the restriking period—an important factor in the reliability of the contact. At the same time, the value of cut-off was never high enough to cause dangerous voltage peaks on the system: such over-voltages as were produced on these tests would be considerably less on an actual system, when the frequency would be lower owing to the presence of the metalclad structure and cables, and in consequence the capacitance would be greater.

Table 9

RESTRIKING-VOLTAGE ANALYSIS

	Test No. 1. 410 r.m.s. symmetrical amps. in arc			Test No. 5. 4 750 r.m.s. symmetrical amps. in arc			Test No. 12. 6 470 r.m.s. symmetrical amps. in arc		
Type of fault	Earthed fault. Insulated neutral			Earthed fault. Insulated neutral			Earthed fault. Earthed neutral		
Sequence of phase interruption	1st	Last		1st	Last		1st	2nd	3rd
	R	B	Y	Y	B	R	B	Y	R
(1) Inherent rate for resistance-damped system	1 000	810	810	3 600	3 130	3 130	5 600	5 000	5 000
(2) Inherent rate (1) corrected for recovery-voltage decrement*	980	790	790	2 620	2 320	2 320	3 820	3 300	3 300
(3) Inherent rate (2) corrected for phase shift due to power factor and asymmetry combined	920	550	550	2 560	2 300	2 300	3 170	3 250	3 250
(4) Actual observed rate	950	750	No record	2 130	2 560	2 400	2 510	2 450	2 620
(5) Cut-off value of current, amps.	4·1	6·1	—	6·0	2·3	0·9	1·7	4·0	2·4
(6) Peak of restriking wave, kV ..	179	117	—	114	81	70	56	87	69
(7) Theoretical max. peak for an infinite 66-kV system ..	162	108	108	162	108	108	108	108	108
(8) Theoretical peak (7) corrected for decreasing power factor and asymmetry of test* ..	145	71	71	114	77	77	63	63	63
Increase of (6) over (8), kV ..	+ 34	+ 46	—	0	+ 4	− 7	− 7	+ 24	+ 6

* The value used is that assuming the machine recovery voltage reaches its 50-cycle value instantaneously without the sub-transient rise noted in some instances.

DISCUSSION BEFORE THE INSTITUTION, 20TH FEBRUARY, 1936

Mr. H. A. Ratcliff: I should like to throw a little light on the origin of the gear described in the paper. It became very evident a few years ago that, if large blocks of energy were to be transmitted and distributed effectively and efficiently in dense load centres such as London and the larger provincial cities, it would be very desirable, if not actually inevitable, to make use of a transmission voltage of 66 kV; this necessitated a review of the position on both economic and technical grounds. There are three principal links in the chain of transmission and distribution: the transformers, the cables, and the switches. Good transformers and cables were obtainable; it was the switches which were the real stumbling-block, as those available at that time were quite unsuitable for the conditions which we had to meet, on account of their colossal dimensions.

There was another equally serious matter to be considered. In London, and to a less extent in the provincial cities, the cost of the site required to accommodate the gear is comparable with the cost of the switches, and in some cases a suitable site cannot be obtained. Moreover, the considerable volume of oil contained in these very large switches entails a substantial expenditure on the provision of effective devices for fighting oil fires which may occur as the result of trouble with the switchgear.

That, then, was the position. Obviously it was a very undesirable position from the point of view of supply undertakings, and it was also obvious that something had to be done to remedy it. We had regard to the very excellent work which had been done by the Electrical Research Association and others, and decided to approach the manufacturers of switchgear on the matter. We explained the situation to them, told them exactly what our requirements were, and asked them to endeavour to break away from their tendency towards the construction of switchgear of excessive physical dimensions. The paper contains experimental proof of the excellence of the type of switch which the manufacturers developed to meet our requirements.

One of the striking features of the paper is the reference to the division of the static potential between the contacts of the multi-break switch. It is not quite certain, however, that those conditions will prevail in switches under operating conditions. The practical success of the switch is doubtless due primarily to the action of the cross-jet pot, and to the authors' very effective means of making contact with the moving portion of the switch.

I think it is very remarkable that the single-break switch has never been developed before. Probably one of the principal reasons has been the difficulty of making effective contact with the moving portion. The double-break switch is a very obvious way of overcoming that difficulty, and consequently the prevailing practice to-day is to employ such a switch.

The two most interesting items in the more theoretical part of the paper are the reference to restriking voltage, and the oscillograph records of arc energy. The arc energy is apparently a function of the current, the arc resistance, and time. It is proportional, I think, to some power of the current less than the square, on account of the physical characteristics of an arc. Although this arc energy is the initial cause of all the trouble, and therefore is a quantity to be handled effectively, it is really a very small quantity compared with the kVA rating applied to the switch. The sooner we abandon kVA ratings the better. It is clearly evident from the test results that the cross-jet pot handles both the arc energy and the restriking voltage effectively.

We naturally thought that if we could reduce the weights and dimensions of these switches the price would probably come down in something like the same proportion. Unfortunately it has not quite worked out in that way, but there has been a very real saving on land and buildings due to the considerable reduction in the space occupied by the switches.

In conclusion, I should like to make an acknowledgment of the valuable work which has been carried out in the switch-testing stations which are now available in this country. I should also like to express the hope that the paper will give an impetus to 66-kV development.

Mr. R. W. Gregory: This paper shows that under test conditions the single-break cross-jet pot type of circuit breaker using the normal earthed metal tank is just about as good at rupturing faults as the double-break cross-jet pot breaker. On the basis of these tests the authors have built and described a form of metalclad switchgear with a single-break circuit breaker which they claim, with some reason, is simpler in layout, lighter in weight, and takes up considerably less room, than double- and multi-break designs for the same duty.

It is this saving in weight and dimensions that to my mind is the main justification of single-break switchgear, as it makes possible a reduction in works cost which should ultimately reach the customer. Switchgear users as distinct from switchgear manufacturers are agreed that switchgear, generally, costs too much for what it has to do, and the supply industry, I feel sure, will welcome any sound design of switchgear that tends to keep the cost low. A power-station switchgear installation at present costs as much as or more than the alternators themselves, which is wrong.

The single-break circuit breaker described in the paper is of the cross-jet pot type, which, like the explosion pot, turbulator, and expansion breaker, makes use of the energy of the arc itself to extinguish the latter and break the circuit. The arc-extinguishing effect is generally a function of the current, and so one finds the curious anomaly that it is much easier with this type of breaker to break a high kVA than a low kVA. This, I think, is indicated by Test No. 13 in Table 5, which shows a small current arc continuing for 27·5 half-cycles and of length equal to the total length of the break of the circuit breaker. Considerable ingenuity has been devoted to improving arc-control devices of this type, in order that the low-kVA arc may be contained and dealt with inside the control device itself.

There appears to be small technical reason why for a given voltage a breaker of the explosion-pot type, of high kVA rating, should not be as cheap as one of low kVA rating, because it is much easier to break the high power than the low, and I visualize in the future a range of circuit breakers rated on voltage only with an upper limit of rated rupturing capacity for each voltage. This would be a very desirable achievement in that it would encourage in the electrical industry the use of voltages proportional to the power to be dealt with.

The curves in Figs. 7 and 10 show the advantage of the single-break over the double-break switch when the arc lengths are long, but when the arc lengths are short the advantage is not quite so great. In my opinion, one of the future essentials of circuit-breaker practice will be that the circuit shall open at very high speed. This high-speed break can, I think, best be obtained along the lines of the oil-blast or impulse type of breaker referred to in the paper, in which the oil is forced between the contacts by some form of outside pressure, not dependent on the arc itself, and at such a rate that the high impulse strength of the oil actually overcomes the rising restriking voltage.

The demand for circuit breakers is a function of the reliability of the apparatus controlled by the breakers. The old solid low-voltage cable systems of years ago were connected to the busbars through ordinary knife-switches. I know of a 6 000-volt system which has been in operation for about 40 years and has had only two faults in that time. A 300-mile 20-kV cable system has about one fault per annum, and the very high-voltage oil-filled cables which are now being used in this country have never yet called upon the circuit breakers controlling them to operate on fault conditions. If every supply system were built upon the basis of good underground cables the need for a multitude of high rupturing-duty circuit breakers would be very much reduced. The real friend of the circuit-breaker manufacturer is the overhead line, which is vulnerable to lightning, fog, dirt, snow, and external mechanical damage, both unintentional and malicious.

In normal times, lightning faults are the most to be feared, and in dealing with them the objective is to cut off the power arc which follows the flashover before it does any damage to the insulation. When this is done the circuit remains healthy and can be immediately re-energized. It has been proved on d.c. railway work that lightning damage is almost entirely eliminated if the power is switched off the line as soon as the flashover occurs, and the use of d.c. high-speed breakers operating at 0·02 sec. between the fault and the clearing has ensured the maintenance of service. One of the ways of attacking the lightning problem on overhead systems in this country is to employ the same methods as are adopted on traction systems, namely very high-speed reclosing breakers; and I am sure that the explosion pot is not the last word in this direction. Treatment of the problem in this way may ultimately result in simplified protection and in a general cheapening of the distribution system.

I am a great believer in metalclad switchgear. It prevents trouble from wandering arcs and conducting vapours, and, in spite of a recent experience, if properly arranged, it will actually reduce the fire risk.

I am fairly certain that if the Hell Gate station in New York had been equipped with metalclad switchgear, properly laid out, there would not have been a "black out" in Manhattan on the 15th January, 1936, nor would there have been any serious damage in the switch-house.

Mr. H. W. Clothier: Four years ago I was apprehensive about the reliability and consistency of operation of boxed-type arc-control devices.[*] Subsequent experiences have justified this fear, but the art is now so far advanced and the design and performance of such devices are so well within control that confidence in them has been established.

I accept the authors' theoretical considerations regarding the distribution of restriking voltage within two arc-control pots as compared with one, and it is possible under certain conditions to obtain as short arc-durations with one turbulator or cross-jet pot per phase as with two in series per phase. The distribution of restriking voltage is, however, only one of the many factors determining the quality of a design.

The paper will help to make users realize the very large amount of research and commercial testing work that is being done in this country with the object of improving the reliability of devices for clearing faults on generating and transmission systems. Not the least important factor in this connection is the rivalry between manufacturers who are aiming at the clearance of faults with minimum disturbance to the system by circuit-breaking in minimum time. Table A establishes a record in recent testing with a single-break oil-immersed circuit breaker fitted with self-generating arc control. The average arc-duration was only 2·2 half-cycles, and the average arc-length was 4·0 in. The results refer to single-phase tests at 57 kV (i.e. $1\cdot5 \times 66/\sqrt{3}$ kV), made at the Reyrolle short-circuit testing-station.

Table A

Current broken	Arc duration	Arc length
amps.	half-cycles	in.
600	2·5	4·75
1 060	2·5	4·75
1 840	2·0	3·55
3 490	2·0	3·55
6 080	2·0	3·55

I question the authors' suggestion of a possible 4 000-MVA performance when ascertained by the synthetic method, which is one of anticipation rather than realization. In Fig. 13 it is shown that with only 600 MVA a tank pressure of 90 lb. per sq. in. is obtained. What may be the tank pressure at nearly seven times this performance?

Horizontal single-break arcing contacts of the plain-break type with magnetic blow-out control within an internal cylindrical enclosure were installed in 1919 in the then largest generating station equipped with metal-clad switchgear,[†] but it was subsequently shown in practice, and proved by testing-station experience, that a better performance was obtained with arc control by means of four plain breaks in series. For voltages of 33 kV and upwards, owing to their longer arcing times, plain breaks are not as good as modern arc-control pots of the cross-jet and turbulator types, but in my opinion plain breaks will continue to have advantages, particularly for heavy-current service on voltages up to 12 kV. As I pointed out in replying to the discussion on my paper at Bristol in February, 1934, circuit breakers with arc-control by 2-break plain contacts have been proved to have consistently short arcing times.* If the efficiency of a circuit breaker is to be judged on the merits of short-time clearance with certainty and consistency of operation coupled with the simplest and most accessible working parts, I advocate draw-out type circuit breakers equipped with 2-break plain contacts.

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[*] *Journal I.E.E.*, 1932, vol. 71, p. 367.

[†] *Ibid.*, 1925, vol. 63, p. 430 and Fig. 7.

Dealing with the types of construction shown in Figs. 11, 19, 20, and 21, the advantages of the single-break arc-control device on 66-kV gear could be obtained just as economically by adherence to conventional designs. For example, in the authors' designs the avoidance of parts moving through oil joints is obtained at the expense of placing the arc-control device upside down. This has the disadvantage that carbon particles and metal globules may settle within the pot and on and around the surface of the bottom insulator. I prefer the orthodox tank construction because it provides more convenient access to working parts, and, as Fig. A shows, the single break does not save so much as might at first be supposed. With regard to the space-saving issue, it is of interest to compare the authors' single-break 66-kV designs with a metalclad construction with orthodox tanks that was in use prior† to the developments under discussion (see Fig. B). It will be seen that little or no saving has been made in space occupied.

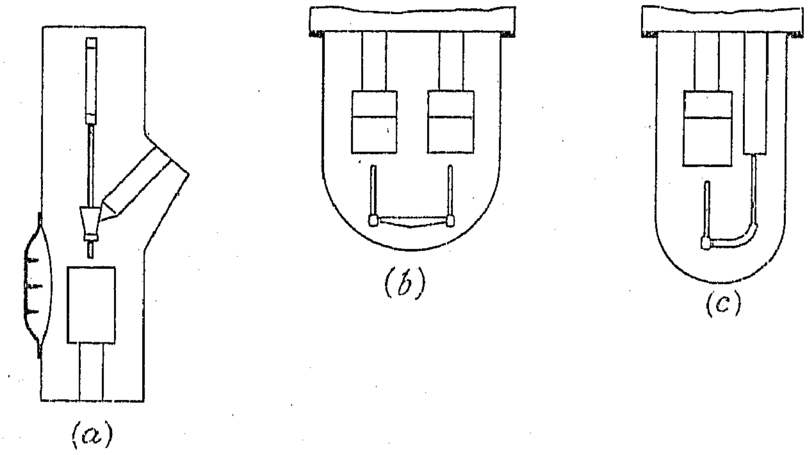
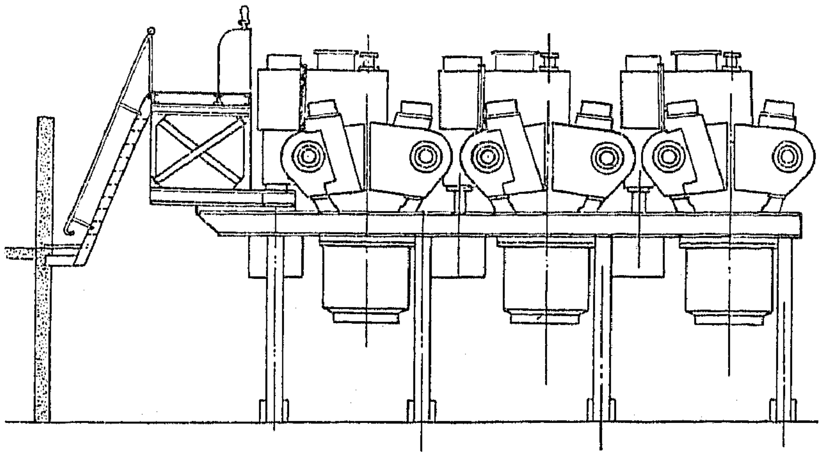


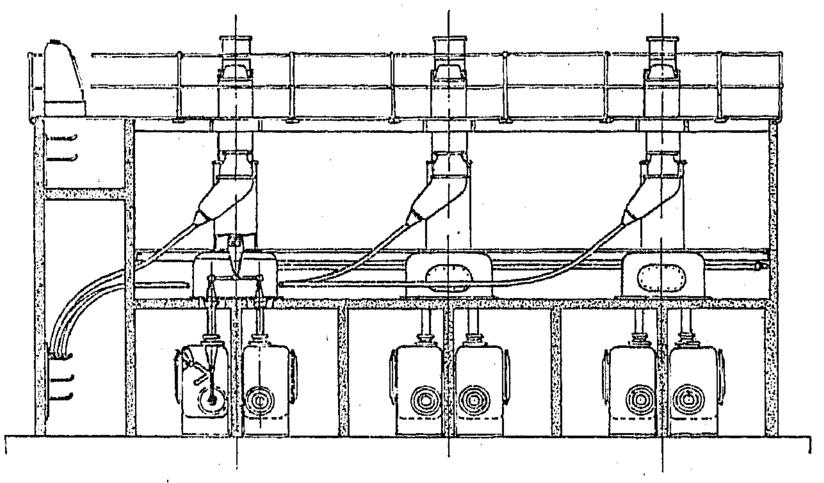
Fig. A.—Various types of oil-immersed circuit breakers.

(a) Fixed-tank type (corresponding to types illustrated in the paper), requiring oil joints.
(b) Removable-tank type, double break, not requiring oil joints.
(c) Removable-tank type, single break, not requiring oil joints.

Two arc-control devices in series are still amply justified on the score of greater convenience in constructional detail. The horizontal rotary moving-contact circuit breaker, shown diagrammatically in Fig. C, is an example of this which also has been proved to give the required reduced arc lengths and arcing times for 132-kV circuit breakers, and it is to be used on the British grid. The arc duration is about 3½ half-cycles at the full rated capacity with 5 cycles total clearing time. Thanks to the disposition of the moving parts, the ratio of the restriking voltages at the breaks is practically constant throughout the travel, and for this reason, as well as because of the comparatively increased tank-clearance, this construction is much more favourable than that shown in the author's Fig. 1.*



Double break (including voltage transformers).



Single break (not including voltage transformers).

Fig. B.—Single-break and double-break 66-kV switchgear with duplicate busbars.

Referring to Table 7, it will be noted that in the break shots the arc duration is reasonably consistent in relation to the arc length. This is as is to be expected, because the relationship is controlled by the speed of travel. On the other hand, however, in the make-break

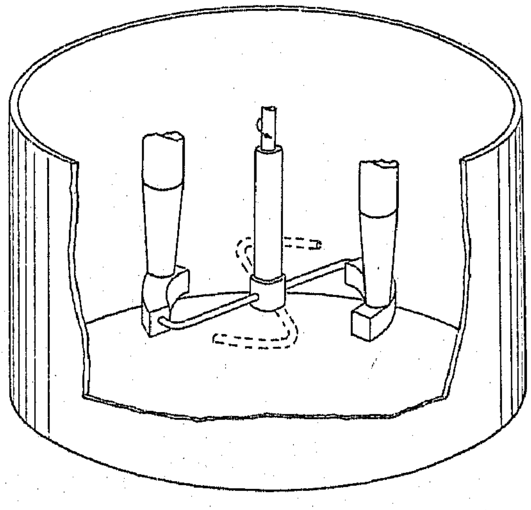


Fig. C.—Diagram showing horizontal rotary moving-contact circuit breaker with turbulators.

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* *Journal I.E.E.*, 1934, vol. 75, p. 656, Fig. GG.
† *Ibid.*, 1932, vol. 71, p. 290, Fig. 21.

* Measurements made since the discussion in London show that the ratio will never be greater than 3 : 1 under the worst conditions.

shots the arc duration is relatively longer; for example, compare test No. 10 (4·2 to 8·1) with test No. 11 (6·2 to 7·5). A corresponding difference does not appear in the tests recorded in Table 8. I should like to have the authors' explanation of these differences. Are they due to some effect upon the speed of travel arising from the closing operation? If so, is the circuit breaker working correctly when it does not close right home? Its speed of break may be handicapped in the subsequent opening operation by reason of the kick-off springs not being fully compressed, resulting in the speed of travel being less than normal. Is this the intention of the designers?

Mr. W. A. Coates: All national specifications to-day call for breaking-capacity tests at full rating only, but, as Mr. Clothier has pointed out, it is characteristic of self-generating arc-control devices that they do not perform equally well throughout their range. It is possible to design so as to obtain optimum performance at any given current. Thus, as is seen from Figs. 16 and 17, the authors' explosion pot performed best at high currents, the arcing time and length increasing as the current decreased. Mr. Clothier has given an example where the reverse was the case. Because arc-control devices of this kind are so commonly used, it is generally accepted by leading makers of switchgear throughout the world that proof tests must be taken at current values from practically the lowest right up to full rating.

In the current British Standard Specification, recovery voltage is introduced merely as one of the factors in the evaluation of performance, and there is no limit on its value. Research work carried out since B.S.S. No. 116—1929 was issued has indicated the predominant importance of the restriking transient, the amplitude of which is proportional to the recovery voltage present at the time of current zero. It therefore becomes essential not only to define a minimum value for the recovery voltage but also to control both power factor and d.c. component. Doubtless at a later date it will be possible to introduce the final factor, i.e. the rate of rise of the restriking voltage.

In the last 18 months the International Electrotechnical Commission has been working very hard on the production of a specification for the short-circuit rating, operation, and testing, of circuit breakers. The work has reached such a stage that within the next few weeks there will be circulated for the National Committees' acceptance a specification, already agreed by the International Experts Committee, which covers short-circuit rating, performance, and testing, but not rate of rise of restriking voltage.

As regards 2-part testing, clearly a synthetic test cannot give the same complete satisfaction to either user or designer as a test taken with full power. If reference is made to Figs. 16 and 17, however, it will be seen that in the range of currents between 3 000 and 10 000 amperes tests have been made at several different voltages, and there is almost no variation of the length of break and the arc duration with the voltage; these quantities vary almost exclusively with the current. This evidence in itself gives a very considerable measure of confidence in the 2-part test, although admittedly if such tests are permitted some limitations must be applied. The authors suggest that when testing firstly with the full recovery voltage and the maximum current obtainable, and secondly with the full current and the highest recovery voltage obtainable, the arc length and arc time must be very nearly the same. With this proviso, the result of such tests should be fairly reliable, because it will be appreciated that, in effect, it rules out the possibility of testing with specially-designed generators having a very steep decrement. The question whether synthetic testing is acceptable is purely one for the industry to determine.

Several speakers have referred to the cost of circuit breakers. If full-power circuit-breaker tests are to be applied, it will mean that testing stations will have to be increased in size, and, of necessity, the price of the circuit breaker will go up. It should be realized that the three largest testing stations in the world are all in this country, but with them we cannot test on full power beyond a rating of 750 000 kVA, although, of course, circuit breakers of double this size are in regular production.

Mr. H. Trencham: I should like to refer to the authors' comments on the inapplicability of gas-blast breakers to metal-enclosed designs. The usual gas-blast designs appear to have ignored the very high insulation value possessed by compressed air, and they are so made that the compression is lost at just that point where high insulation is wanted, i.e. in the interrupting nozzle. If this defect would admit of correction an enclosed design should be possible.

I am not quite satisfied as to the meaning of "restriking voltage." It has been variously expressed as rate of rise in volts per microsecond and as a natural frequency, neither of which tells the whole story because amplitude is ignored. With a fuller knowledge of wave-shapes, the significance of their differences should be ascertainable and we might then be able to determine rationally the maximum voltage which can be interrupted on one break. It may well be, as the authors imply, as high as 132 kV.

The firm with which I am connected has recently been successful in producing an instrument which will show as a visible trace a standing wave giving the form of the restriking voltage wave which occurs inherently at any point on a system. That instrument is now being tested on a circuit-breaker test plant for operation close up to a machine. I am satisfied that with a device of that kind we shall be able to make substantial progress in our knowledge of the action of the restriking voltage.

I agree with the authors that the single-break switch is not well adapted to low-voltage designs. I am not without hope, however, that when we get to know a little more about it we may find methods of applying the single-break design even to low voltages. Whether it is applied to low voltages or to high, however, I feel that some of the difficulties indicated by another speaker would be met by adopting a horizontal movement instead of a vertical one. The breakage of an insulating rod could not then result in the breaker falling into contact accidentally, and leakage from bushings could not occur, as a single-break switch of this kind could be housed in a tank having no joint in the bottom.

The authors mention the choice between a removable and a fixed breaker; I prefer the former. If a piece of equipment can be taken to pieces there is, in the unfortunate event of a mishap, a better chance of quickly discovering the defect and of readily putting it right.

(*Communicated*) The scope of the instrument mentioned above for indicating the form of restriking voltage waves will be better appreciated from the accompanying photographs, taken with an ordinary camera, of standing wave shapes recorded on the instrument.

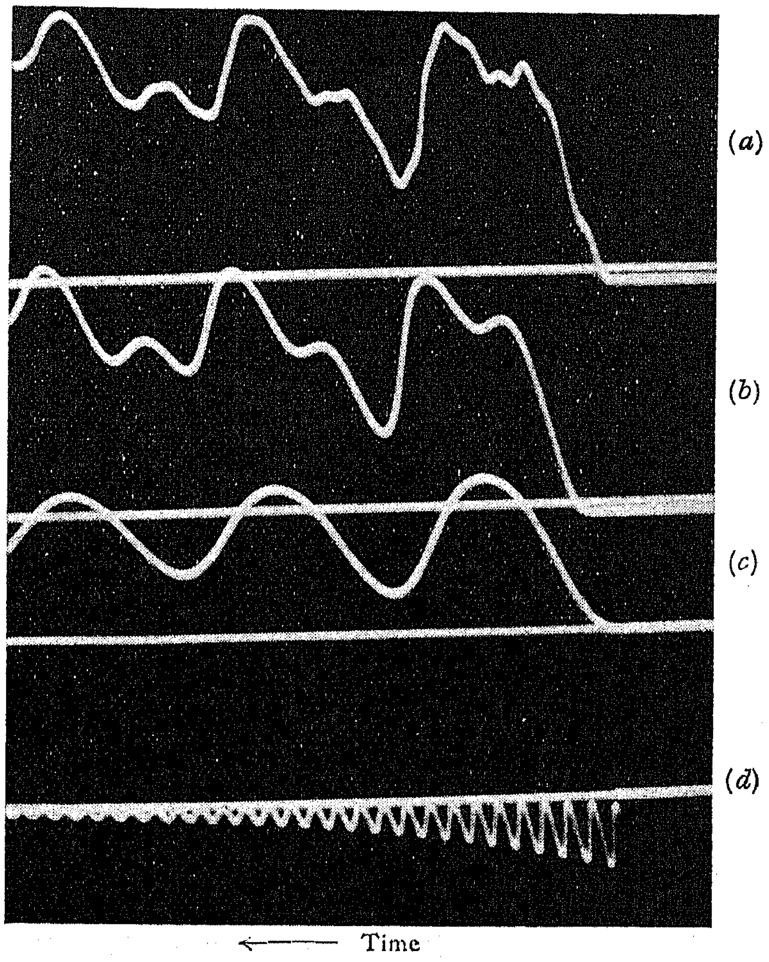

Fig. D.—Artificial restriking-voltage waves.

Fig. D was obtained from a laboratory set-up; (*d*) is the 197-kc timing wave, and (*c*), (*b*), and (*a*) are the voltages appearing across a break with an artificial circuit having one frequency, two frequencies, and three frequencies respectively.

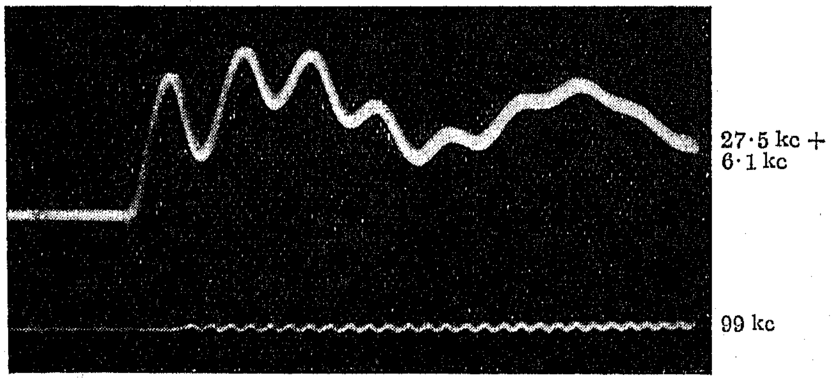

Fig. E.—Restriking-voltage wave of test generator with reactors in series.

Fig. E was taken in a circuit-breaker testing station with the testing generator and current-limiting reactors in circuit. The steadiness of the wave is evident from the fact that the first picture was given a 20-sec. exposure.

Mr. A. K. Nuttall: There are a few remarks which I should like to make in connection with the calibration of the potential divider used in measuring the cross-arm potential (Fig. 6). The capacitance of the high-voltage side of this divider is of the order of 10 $\mu\mu$F, and that of the low-voltage side is also small, of the order of 200 $\mu\mu$F. In view of the errors which might occur in the recording of this potential, owing to possible errors in the measurement of these capacitances, it was decided to calibrate this potential divider directly.

The most obvious way of doing this is to apply a known 50-cycle voltage to the cross-arm and to measure the amplitude of the resultant record on the cathode-ray oscillograph. The question arises, however, whether such a calibration is valid for the frequencies and the rates of rise of voltage which occur during or subsequent to the act of restriking. It will only be valid if the potential divider is a pure capacitance, and this is a matter which requires considerable investigation.

It is easy to calculate the effect of a leakage resistance across the plates of the oscillograph, which, together with the connection to the small bakelite bushing described, constitute the low-voltage side of the potential divider. Calculation shows that the ratio of potential division when a resistance of 25 megohms is connected across the plates is greater at 50 cycles per sec. than at 100 000 cycles per sec. in the proportion of 1·17 to 1; so that if there is a leakage resistance of this value across the plates, the apparent value of the high-frequency component of the restriking voltage existing on the cross-arm, as calculated from the recorded amplitude and the 50-cycle calibration of the potential divider, will be high in the same proportion. If the leakage resistance be decreased to 5 megohms, the proportional error will be increased. In normal conditions, tests made on the leakage resistance of this part of the system always gave values well in excess of 100 megohms, so that theoretically one may expect no errors from this source.

The danger of this leakage resistance was well demonstrated by tests made on a very foggy day when the insulation of the lead connecting the potential divider to the oscillograph was covered with copious deposits of moisture and industrial dirt. The records taken on this occasion showed a restriking voltage having an amplitude abnormally high compared with that of the subsequent normal-frequency steady-state voltage, and this effect was confirmed on a dry day by placing an artificial leak of 5 megohms across the oscillograph plates, when the results agreed very well with the calculation which had been made.

Since this potential divider was to be used for the measurement of restriking voltages, the final calibration was performed by isolating that side of the breaker which is earthed under normal test conditions, closing the breaker, and closing the master breaker, the generator voltage being set at a value well within the range of the cross-arm potential divider. Two simultaneous oscillographic records of the resulting voltage impulse are obtained, one by means of the cross-arm potential divider, and the other by means of the divider normally used for determining the voltage occurring across the whole breaker. One can thus obtain the direct calibration of the cross-arm potential divider for transient and high-frequency conditions almost identical with those under which measurements are required to be made. It was found, on making this calibration, that the ratio of potential division was substantially independent of frequency, thus justifying the use of this potential divider for the measurement of restriking voltages.

Dr. W. B. Whitney: Mr. Trencham has referred to the restriking voltage and the importance of being able to measure it in field networks. The Electrical Research Association has been entrusted with this investigation and now possesses a portable recording equipment which is ready for use wherever supply authorities can offer the necessary facilities on their networks.

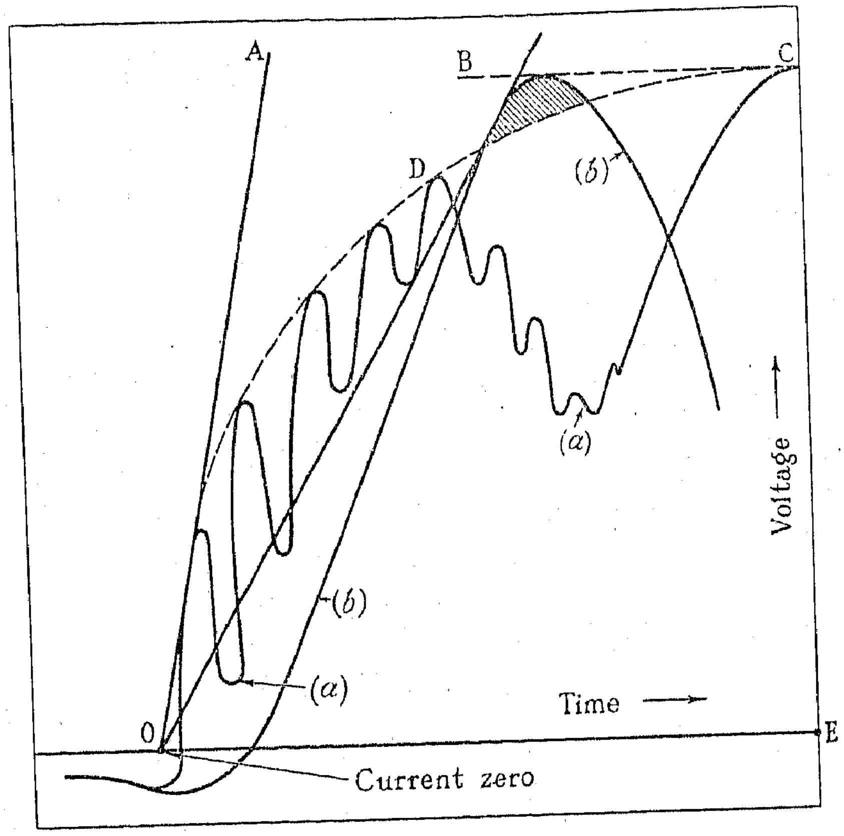

Fig. F

Figures for the rate of rise of restriking voltage are given in connection with most of the authors' oscillograms, and represent the slope of the steepest tangent to the restriking-voltage curve from the instant of zero current. In America and elsewhere the rate of rise is now often taken as an indication of the circuit severity in relation to the breaker; the higher the rate of rise the greater the severity, and vice versa.

I should like to draw attention to a difficulty which can occur when one is using the method of interpretation of the rate of rise of restriking voltage adopted by the authors, or in using any other tangential method with which I am acquainted. The tangential method has, for some practical purposes, much to recommend it, but it may occasionally lead to the unexpected result that a circuit with a higher rate of rise, as measured in accordance with the authors' description, is easier to break than one with a lower rate. Thus if the line ODC in Fig. F represents the electric-strength/time curve for the arc gap just after current zero, so that any part of a restriking-voltage transient rising above ODC is in a region of instability where breakdown may occur, the transient marked (*b*) is more likely to cause breakdown than the transient marked (*a*), because (*b*) rises above ODC (see hatched portion). OB, the tangent to (*b*), is, however, less steep than OA, the tangent to (*a*), or, indeed, than any of the tangents which might be drawn from O to the four other peaks of (*a*) which are above the line OB, thus giving the apparently anomalous result referred to above.

(*Communicated*) In measuring the rate of rise of restriking voltage the authors seem quite satisfied to draw the tangent to the first peak of oscillation, irrespective of any consideration of the possible shape of the electric-strength/time curve for the gap or of the proportion which this voltage bears to the final voltage (e.g. the

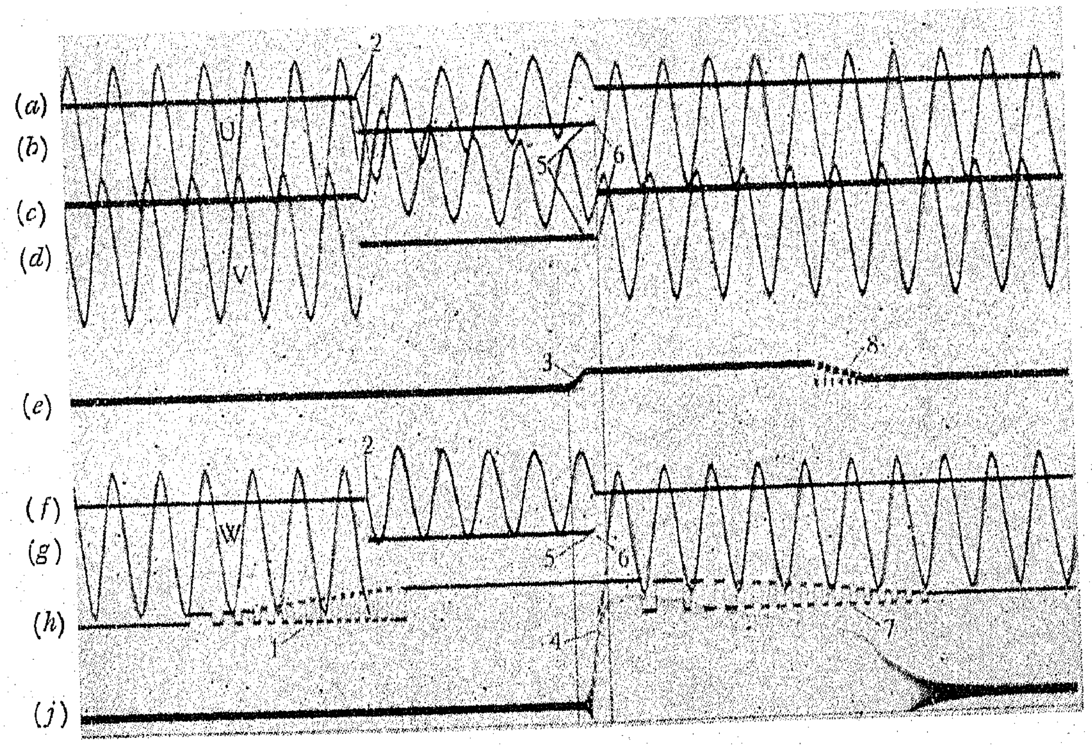

Fig. G.—Oscillogram of 3-pole closing and opening operation performed by 50-kV air-blast high-speed circuit breaker on 50-cycle supply. (The breaker closed on 745 MVA and opened on 550 MVA, the arc duration being about ¼ cycle.)

two oscillograms in Tests 9 and 10, Fig. 8). The method of measuring rate of rise of restriking voltage by a tangent may be useful in the case of oscillations such as those shown, for example, in Tests Nos. 8 and 12, Fig. 8. Here the restriking voltage reaches its highest peak in the first oscillation and restriking cannot, therefore, take place so long as the tangent to this curve is flatter than the electric-strength/time curve of the gap. The tangents to the oscillograms in Tests Nos. 9 and 10 (Fig. 8) are, however, in a very different category, and the use of the tangent method with wave-fronts of this type, which have a number of oscillation peaks of increasing magnitude, may easily lead to anomalous results, as indicated in the example shown in Fig. F.

A further matter that needs attention, if discussions and definition of rate of rise of restriking voltage are not to end in confusion of thought, is the question of the method of deciding from what point, on the zero line of voltage, the tangent to the wave-front is to be drawn. Clearly the authors have tried to select this as the point at which the current through the arc gap reaches zero, but the points thus chosen seem somewhat arbitrary [e.g. Figs. 3(*a*) and 3(*c*); Test No. 12, Fig. 8; and Fig. 23(*c*)].

Mr. Basil Wood (*communicated*): The gas-blast breaker has been mentioned in the discussion, and Mr. Trencham has suggested that it might be possible to attain by its use shorter arcing times than with conventional oil circuit-breakers if the high insulating properties of compressed air were realized, and fully utilized. These possibilities have already been commercially realized in a type of air-blast high-speed circuit breaker, of which a large number of units are in service on the Continent, having a guaranteed and proved arcing time of ½ cycle or less. This performance is obtained by suitable control of the arc length and by the concentration of the air blast on the arc.

Fig. G shows an oscillogram for such a breaker clearing 550 MVA at 50 kV, with an arcing time of about ½ cycle. Trace (*e*) shows the movement of the blast valve, (*h*) that of the isolators, and (*j*) the air-blast pressure at the arc. It should be mentioned that tripping of the breaker after closing on the short-circuit was delayed deliberately for about 6 cycles, in accordance with I.E.C. recommendations, in order to allow the asymmetrical component to fall to a small value. This design, whilst achieving the desired end of abolishing entirely the use of oil in circuit breakers, has improved on the operating times obtained consistently by even the fast oil circuit-breakers described in the paper.

[The authors' reply to this discussion will be found on page 171.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 24TH FEBRUARY, 1936

Mr. W. A. Coates: The authors make no mention of one advantage incidental to the single-break construction, namely the freedom from electromagnetic forces acting on the moving elements. Breaking-currents of 50 000 amperes or more are common, and in the conventional double-break circuit breaker the forces on the moving contact may amount to several tons. The effect occurs just at the moment when the closing mechanism commences to compress the accelerating springs, and the solenoid has to close the circuit breaker under these conditions. In consequence, it is extremely difficult to secure latching when this is essential, or in the more usual case to prevent the contacts welding during the short time-interval before automatic protective gear operates to release the trip-free device.

In the authors' single-break circuit breaker there is no loop circuit, and therefore electromagnetic forces.

The authors claim that their experimental work has demonstrated that a double-break circuit breaker of conventional type would need to have two breaks, each as long as the one break in their new design. The data presented make it fairly clear that this is the case, but to obtain practical support I have analysed the test results on a double-break 66-kV circuit breaker fitted with cross-jet pots very similar to those employed during the tests recorded in the paper. No low-current tests had been made on the double-break construction, so that, in view of the lengthening time and stroke at low-current values shown in Fig. 17, comparison has been made only with the tests taken at breaking-currents of 500 amperes or more. Taking the average of the 24 tests recorded in the paper with voltages of 50 kV and upwards, it would be found that with the single-break design the arcing time was 4·1 half-cycles and the length of break 7 in. On the double-break circuit breaker, 41 tests coming within the same current and voltage ranges give an average arcing time of 9·1 half-cycles and an average length per break 5·9 in., or a total of 11·8 in. per phase. The tests on the double-break circuit breakers were taken on a test plant other than those referred to in the paper, but one of comparable size, and the results give very valuable practical support to the authors' contention.

A further point of considerable interest is the method of stating the rate of rise of restriking voltage. A few years ago Mr. Clothier introduced to the Institution the idea of employing a severity factor in testing circuit breakers.* This was an attempt to take into account not only the normal-frequency recovery voltage (which has been recognized as desirable for several years) but also the modification in that voltage by reason of the displacement of the current wave and the power factor of the system. Finally he suggested introducing the natural frequency of the system or the rate of rise of the transient wave. I submit that it is incorrect to term this a "severity factor," because the variations in performance on different types of circuit breakers will not consistently follow changes in this factor. It is nowadays well known that with circuit breakers which are positive in their action, e.g. the impulse type, increasing the amplitude and rate of rise of restriking voltage does not alter the arcing time until this increase reaches the point where it causes failure. On the other hand, with a plain-break circuit breaker increasing these values does, broadly speaking, increase the arcing time. Those of us who are concerned with standardization of testing methods might be appreciably assisted by suggestions for an alternative term which could be applied to this factor. Tentatively, the term "weighted recovery voltage" might serve.

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* *Journal I.E.E.*, 1932, vol. 71, p. 285.

Finally, it may be well to point out the varying bases which have been suggested for stating the rate of rise of restriking voltage. In Figs. H and J there are reproduced two of the restriking waves shown in the paper, and Fig. H shows the three methods sometimes adopted. The only significance attaching to the rate of rise of the restriking wave is in comparison with the rate at which electric strength is re-established between the contacts. On this point we know very little as yet, but it seems obvious that since the re-establishment of electric strength must start from the instant of current zero, there is no point in stating the maximum rate of rise as given by the tangent M M′. Equally it seems inadvisable to state the mean as given by the line O B. The majority of workers in this field have adopted the convention used by the authors, and have stated their rate as the slope of a tangent drawn from the current-zero time, as at O A.

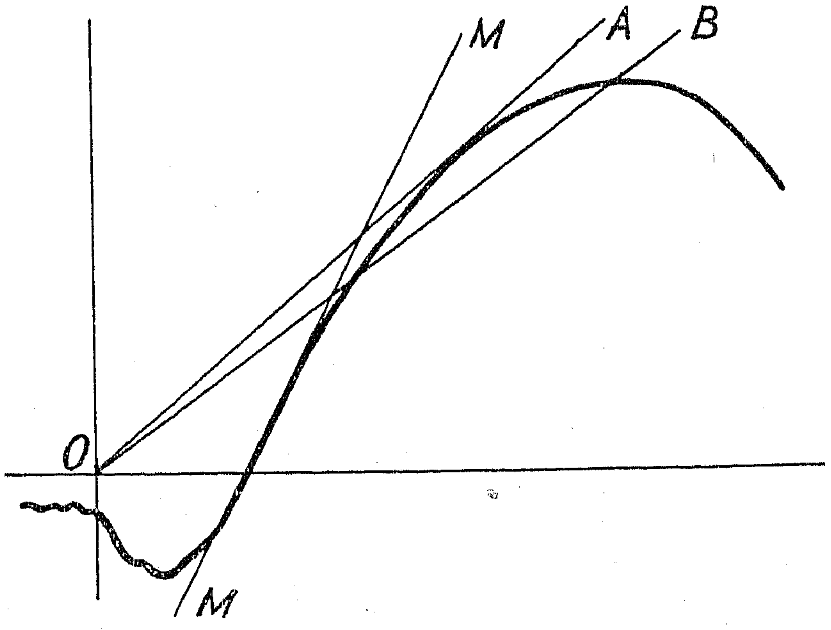

Fig. H

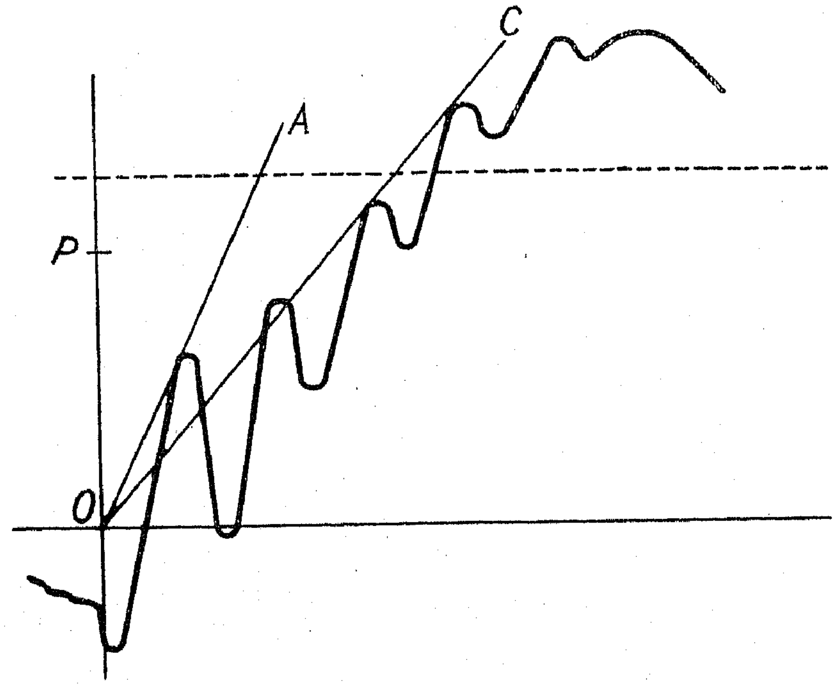

Fig. J

Broken line denotes peak value of 50-cycle recovery voltage.
P denotes 80 per cent of 50-cycle peak.

There is one further convention, which has been suggested in the United States and is illustrated in Fig. J. This concerns restriking waves caused by multiple natural frequencies, in which case there will be harmonics on the fundamental transient. In the example, the first tangent would be the line O A, but since the amplitude of this preliminary ripple is low, it is fair to assume that it would not suffice to cause permanent breakdown of the dielectric between contacts. The American convention is, therefore, to draw the tangent to the first portion of the wave, the amplitude of which exceeds 80 per cent of the peak of the normal-frequency voltage, thus giving the line O C. It would seem desirable for us to employ the same convention in this country, until such time as more is known concerning the restoration of electric strength between contacts.

Mr. A. Allan: As the authors remark, single-break switches are by no means new; metalclad switches of this type were manufactured in this district over 15 years ago, but their development has undoubtedly been retarded to some extent by the difficulty of disposing the incoming and outgoing connections conveniently in metalclad gear, whilst retaining the draw-out feature which has rightly become so popular. The authors have evolved a number of ingenious applications of a single break, but to obtain compactness they have, at least in some of these designs, abandoned the draw-out feature and adopted a built-in type of switchgear in which accessibility for maintenance has been to some extent sacrificed. Whilst it is true to say that the modern switch requires only infrequent attention, I think, nevertheless, that most engineers will not easily be persuaded that it is safe to allow men to work on parts of built-in switchgear within a few inches of conductors alive at 66 000 or 132 000 volts, and for this reason the completely removable unit must always have a greater appeal. Rather than decrease the maintenance facilities, the ideal would seem to be to make withdrawable not only the circuit breaker but also the isolating switches, so that, if required, practically the whole panel could be removed, leaving only the busbar and feeder chambers.

This ideal has been achieved in respect of the circuit breakers and their isolators in 132-kV metalclad equipment which has been in service for some years at Tongland substation in the South of Scotland. The circuit breakers in this equipment are provided with sliding bushings which serve to isolate them from the fixed connections. These bushings are withdrawn downwards towards the circuit-breaker tanks, so that the circuit breakers, complete with their isolating bushings, and the isolator operating mechanism, may be withdrawn horizontally for inspection or maintenance when required. The sliding bushings are operated by oil pressure, the construction being as illustrated in Fig. K. In the Tongland equipment, owing to the fact that the circuit breakers are connected in mesh, certain isolating switches are located in the non-withdrawable portion, but these fixed isolators can be individually maintained without the loss of more than one feeder or one transformer. When the breakers are used in conjunction with duplicate busbars, the whole of the isolators are incorporated in the removable circuit-breaker unit. This construction is illustrated in Fig. L, which shows also, to the same scale, single-break equipment of the built-in type which has been developed by the authors. The draw-out type employs two rotary breaks per phase, but, in spite of the saving claimed by the authors in employing a single-break unit, and the sacrifice of maintenance facilities, it will be seen that the built-in type of gear occupies a far greater volume than the draw-out type illustrated. Unfortunately, the authors do not indicate the scale to which their drawings have been made. Fig. L has been based upon Fig. 19 in their paper, which appears to have been drawn for a working voltage of 66 kV, although it is described as being suitable for voltages up to 132 kV. In preparing the present illustration for comparison purposes, in order to retain minimum dimensions it has been assumed that the cross-jet pot would be no larger in diameter for 132 kV than for 66 kV, and only the minimum clearances in the oil-filled chambers have been allowed in determining the dimensions.

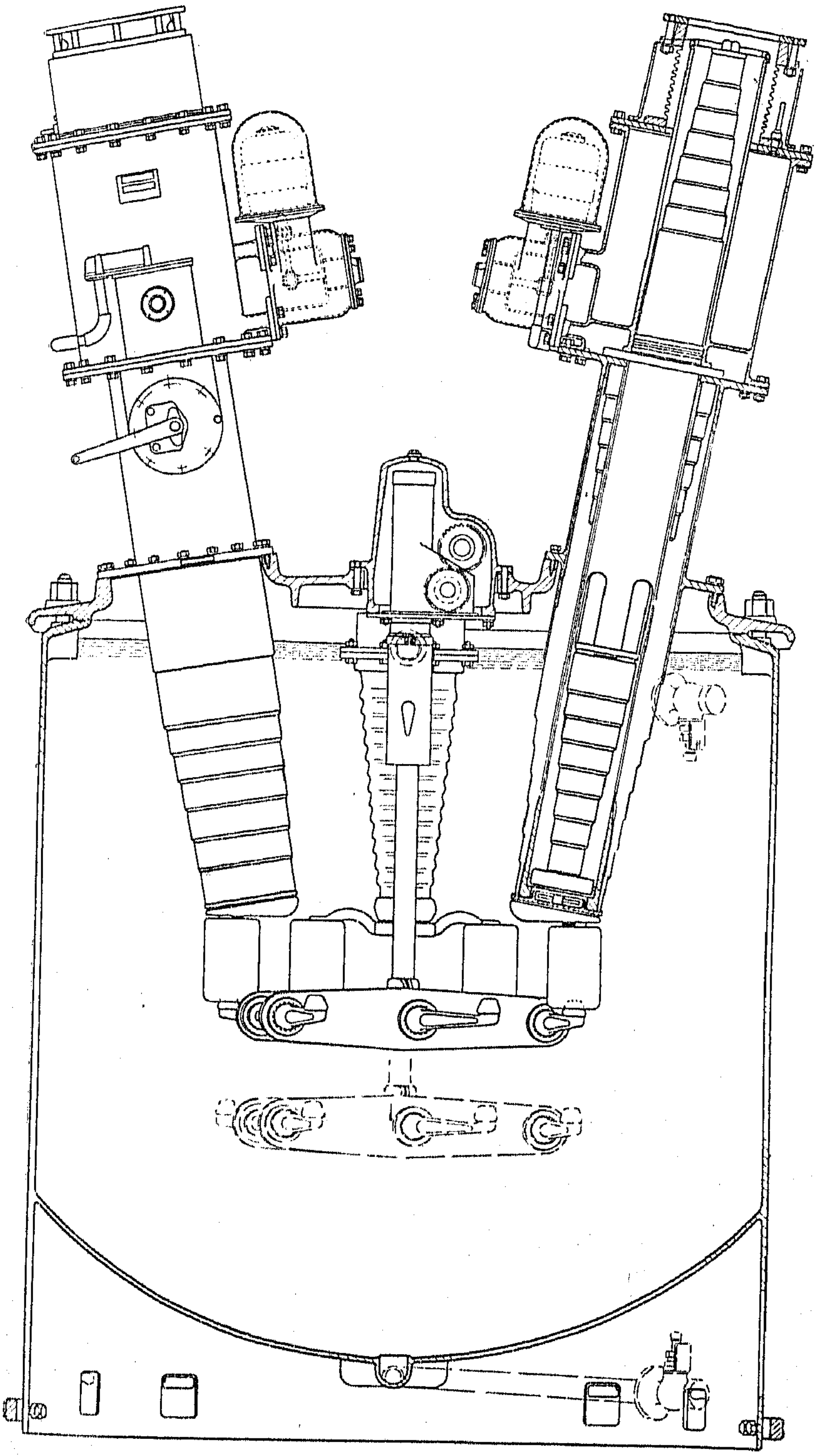

Fig. K.—132-kV metalclad draw-out circuit-breaker unit, complete with sliding bushing isolators.

The volume occupied by the draw-out type is 6 200 cub. ft., including the draw-out space, whilst that occupied by the built-in arrangement is approximately 14 000 cub. ft. The floor area occupied by the draw-out arrangement is 390 sq. ft. per panel, and that for the built-in arrangement is 530 sq. ft. The space occupied by the built-in type would be reduced to about 12 000 cub. ft. with a floor area of 440 sq. ft. by the omission of the walls separating the individual busbars, but even then the draw-out type would still show a considerable saving in space. This result is achieved by the sliding-bushing construction, which obviates the large oil-filled chambers necessary for the blade type of isolator employed in the built-in design. Moreover, with the sliding-bushing construction earthed separation is provided between the duplicate busbar connections, whereas in the built-in construction connections from both busbars are brought into a common chamber. In addition, with the draw-out type any set of busbar isolators can be maintained without the necessity of shutting down either busbar.

I suggest that in concentrating their attention upon reducing the size of the circuit breaker by the adoption of a single break, the authors have rather ignored the fact that the necessary facilities for isolating the circuit breaker form a larger proportion of the total space occupied. The comparison to which I have referred indicates that much greater saving in space can be effected by suitable construction of the isolating features than can be achieved by departing from the more orthodox design of circuit breaker in which the contacts are readily accessible by removal of or from the tank. That the adoption of a single break does not necessitate the sacrifice of this feature is indicated by Fig. M, which illustrates a single-break 11-kV circuit breaker having the orthodox vertical drop-down feature for isolation, and a removable tank for contact inspection. This type of circuit breaker has been proved by short-circuit tests up to a maximum current of 13 000 amperes (r.m.s.). Each phase is provided with a single arc-control device, these being disposed in plan at the corners of an equilateral triangle, so that each phase has its equal share of the cylindrical tank. The incoming and outgoing bushings are arranged concentrically on each phase.

Mr. D. Adam: I was privileged to witness several of the single-break tests mentioned in the paper, and I can confirm that the breaker gave a very good performance. I have also witnessed similar tests on arc-control devices fitted to double-break circuit breakers, and these also gave very good results. There is little doubt that, with correctly designed arc-control devices, good performance can be obtained.

It seems to me, therefore, that the problem is not so much one of deciding whether the single-break switch is preferable to the double-break, but of reducing the arc length and arc duration to a minimum. In this respect it is interesting to note from Figs. 7 and 10 that, if the arc lengths can be reduced still further, the distribution of duty over the double-break breaker is more nearly uniform, and thus the justification of the single-break type is not so pronounced.

It is stated in the paper that no difficulty is anticipated in constructing a single-break circuit breaker to deal with any voltage at present used in this country. I should like to ask the authors whether this statement applies to 132-kV working, as it seems to me that a single-break switch for this voltage may not be easy to achieve. In general, a higher voltage usually means longer arc duration, and in order to reduce the arc duration it would seem necessary to put up the speed of break considerably. Increasing the speed of break may quite easily increase the actual arc length, and, in order to keep the arc within the pot, either the arc-control device will have to be more efficient or else the pot length will have to be increased. A larger pot implies more oil, and the increased inertia will tend to slow down the cross-blast action.

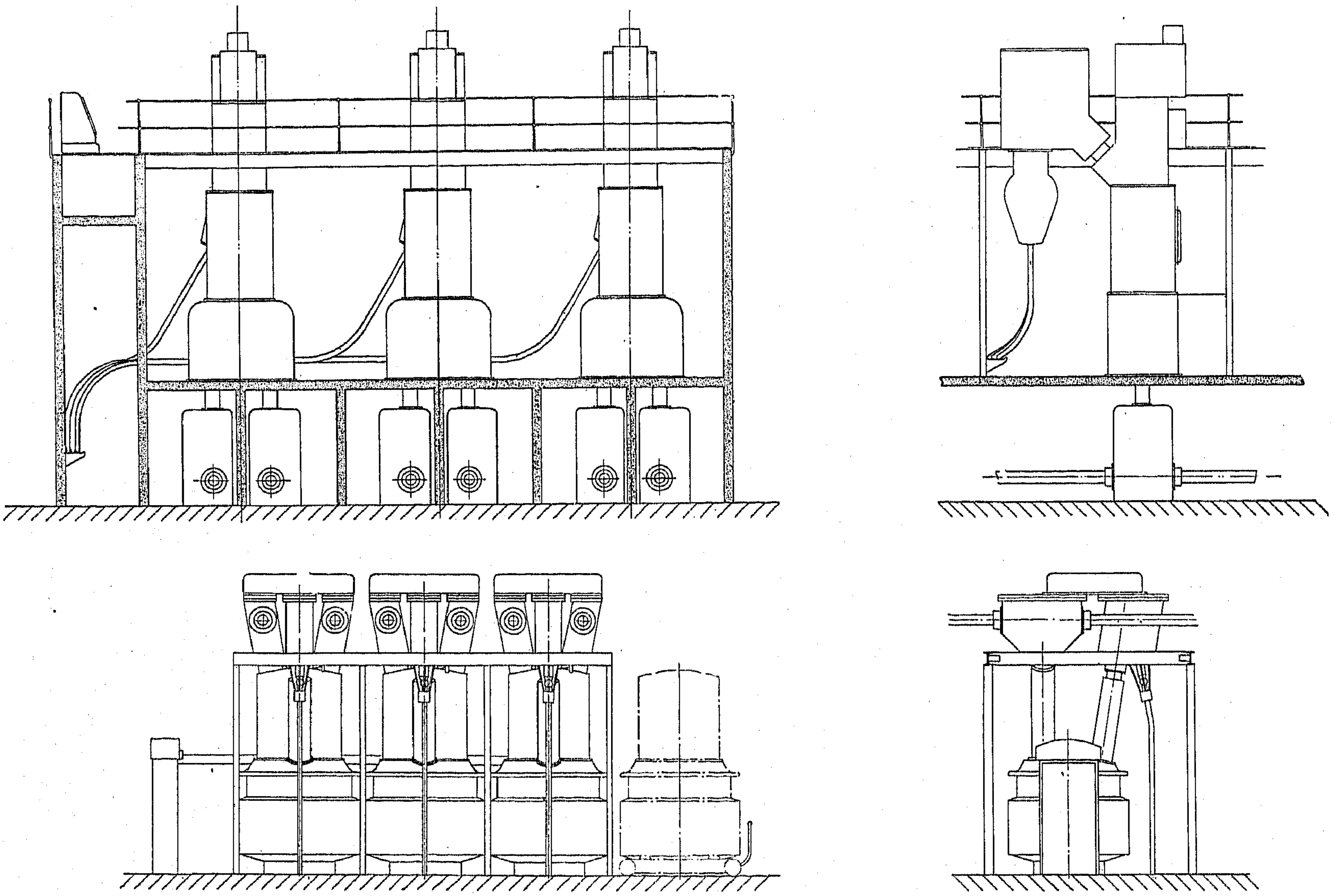

Fig. L.—Comparison of 132-kV metalclad switchgear.

Above: Single-break built-in type.
Below: Double-break draw-out type with withdrawable isolators.

The second point which I have to raise is concerned with the rate of rise of restriking voltage. In their results of tests the authors very rightly give both the rate of rise of, and the maximum value of, the restriking voltage. Both these factors are of great importance, and both must have a vital bearing on the re-establishing of the arc voltage. Have the authors been able to correlate these two factors? Taking purely hypothetical figures, we may have on the one hand a very high rate of rise of restriking voltage such as 3 000–4 000 volts per microsecond and a comparatively low peak value of restriking voltage such as 3 000–4 000 volts, when the rate of rise would not appear to matter very much. On the other hand, we may have a comparatively low rate of rise such as 100 volts per microsecond, but a very high peak such as 40 000–50 000 volts, when presumably the rate of rise would vitally affect the problem.

Mr. R. W. L. Harris: I should be glad if the authors would amplify the brief reference they make to the question of synthetic tests. On the larger types of circuit breakers which cannot be tested directly at all the required combinations of current and voltage conditions, the synthetic method is the only one that can be employed, but mention is made in the paper of a factor of safety which must be allowed when assessing ratings in this way. It would seem that this must detract considerably from the reliability of the conclusions reached, even if the breaker operated consistently throughout the tests.

It would enhance the value of the paper if the authors would give their considered opinion of the conditions which should be imposed as regards equality of arc lengths, arc durations, speed of breaker, and other

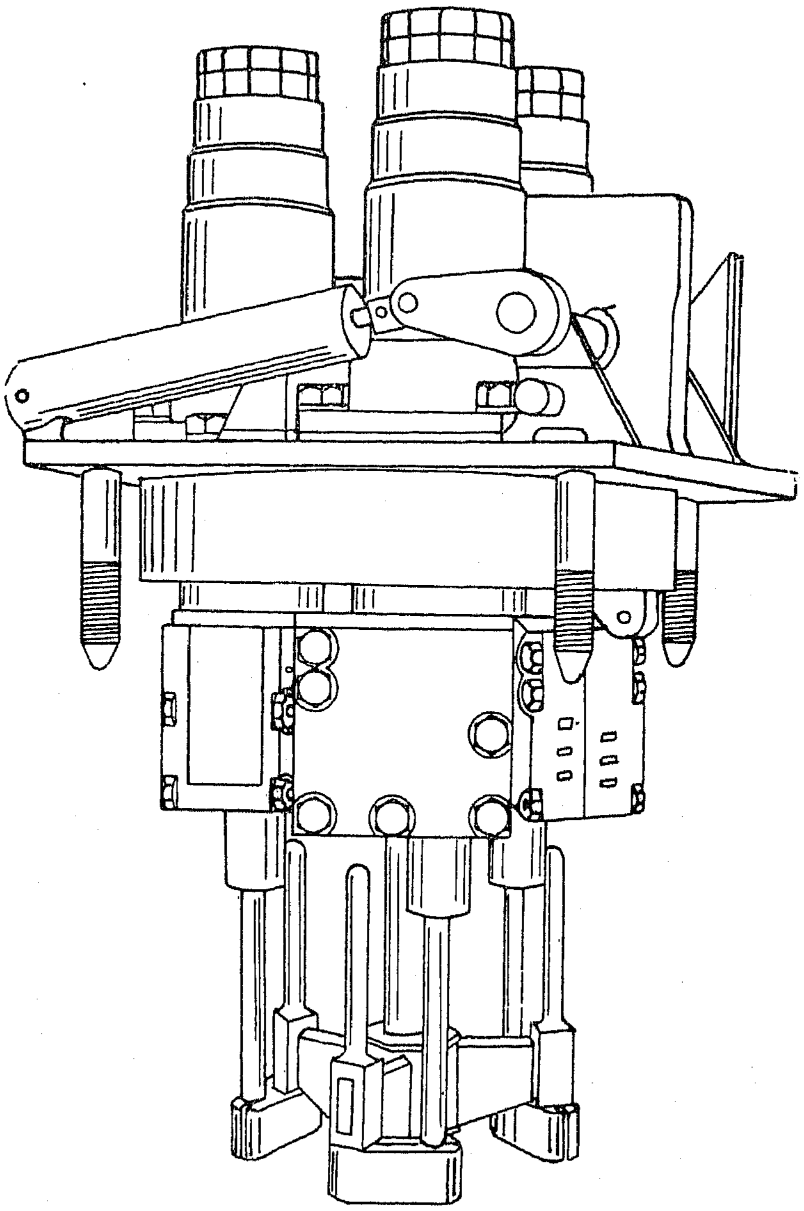

Fig. M.—Single-break withdrawable circuit-breaker with removable tank.

similar factors, when carrying out two series of tests, one at high voltages and the other at high currents, on different types of breakers for combining synthetically.

In the illustrations of switchgear designs incorporating the single-break feature, a large number of compartments are shown containing a fluid insulating medium; these must necessarily introduce a number of attendant difficulties, especially as regards maintenance. It is not quite clear from Fig. 21 whether the oil systems are all entirely independent of one another, or whether, for example, the busbar-selector chamber and current-transformer chamber are maintained under the head of oil in the chamber containing the tee-off connections to the duplicate circuit breakers.

Mr. W. A. A. Burgess: In their verbal résumé of the paper the authors made reference to "magnetic latches." What is meant by this expression?

Mr. H. G. A. Stedman: Those who have had many years of operating experience with high-voltage circuit breakers will, I think, agree with me that any development which aims at reducing the amount of oil contained in the oil circuit-breaker is a step in the right direction. The diagrams in the paper rather suggest, however, that the authors' single-break switchgear may not prove as satisfactory from an operating and maintenance point of view as the more orthodox designs.

It appears to me that the multiplicity of the nuts which have to be removed to get the various doors off is a decided drawback; and the possibility of oil leakage, from at least 6 or 8 different points, must not be neglected. Further, on closing, one may have trouble with the contacts. It is not easy to see how the "pots" or extinguishers function as arc-suppressors, and I hope that in their reply the authors will be able to demonstrate the action of these devices more clearly.

[The authors' reply to this discussion will be found on page 171.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 25TH FEBRUARY, 1936

Mr. A. R. Blandford: The object of the paper is to prove that the orthodox circuit breaker as we know it, with two breaks, has very little advantage when compared with a single-break circuit breaker. The reasoning is based upon the distribution of capacitances between the moving contacts and the fixed contacts, and between the moving contact and the tank. It is stated that capacitance measurements were made on a conventional 2-break circuit breaker fitted with cross-jet pots. I suggest that one should be very diffident in taking figures given by the authors as being standard figures that can be applied to any oil circuit-breaker, as any appreciable variation in the capacitance between the fixed and moving contacts will materially alter the figures given in Table 1.

I know of no better method of controlling the capacitances than by means of the arc-control device itself, which, in the case of one well-known type, lends itself readily to the incorporation of electrostatic control. This practice has been applied to high-voltage circuit breakers for voltages as high as 132 and 220 kV.

On page 133 the authors state: "A second series of tests were made on a 33-kV metalclad breaker fitted with a specially constructed capacitance divider, which increased the capacitance to earth of the moving contact by only 12 $\mu\mu$F." Seeing that the values they are dealing with in their tests are only of the order of 10 and 40 $\mu\mu$F, I consider this quite a reasonable percentage variation.

Referring to the short-circuit test data, I am disappointed to find that no reference is made to the difference obtained in arc energy as between the single- and double-break breakers. The arc energy is a criterion of the deterioration of the oil and the contacts, by which a circuit breaker may be judged.

While, as shown by the authors, in a double-break circuit breaker the voltage across one break may only be a small percentage of the total voltage, I am in favour of retaining the second break to assist in reducing the voltage gradient across the break, and to aid in rapid arc extinction. In addition, assuming each break of a double-break breaker equivalent to the break of the single-break breaker, it can be claimed that the former has double the safety factor of the single-break breaker.

Dealing with the mechanical design of the breaker, the authors have made a step forward in that they have succeeded in cutting down the oil quantities. They point out that one can get very much higher speeds with the single break than with a double break, owing to the reduction in the mass of the moving parts. I would rather say that with the single break very much higher speeds are needed, because the speed of break for a given speed of travel can only be half of that with a double-break circuit breaker, and this deficiency has to be made up in some way.

The authors' slides showed that quite a number of mechanical joints are under oil in the tank. These joints are subject to pressure impulses and high stresses. Further, to examine the breaker it is necessary to drain the oil and break the oil-tight joint, and after examination to remake the joint and refill with oil. It is very difficult to guarantee a joint when first made as being oil-tight, and consequently there is a great risk of oil leakage from such a joint, especially when it is remembered that it may have to be remade under emergency conditions.

In my opinion the accessibility of the authors' design does not compare with that of the orthodox breaker where the tank can be lowered for the purpose of inspection. In the circuit breaker described in the paper, when the door of the tank is opened all there is to be seen is the outside of the arc-control device, and it appears that a certain amount of dismantling would be required to inspect the contacts, and the dismantling would have to take place at a point which is difficult of access.

Another disadvantage is the sliding type of contact incorporated in the design. It appears that this contact needs to exert a certain pressure or friction on the arcing contact, which, under rupturing-capacity conditions, would tend to reduce the speed of the breaker.

The authors' breaker differs from most double-break circuit breakers in that there is no magnetic effect tending to increase its speed under opening conditions, and presumably this could only be compensated for by piston effect from the arc-control device.

Finally, the breaker has been so designed that failure of any mechanical part may tend to cause the circuit breaker to fall into contact.

Mr. W. Kidd: I have had the privilege of seeing, in various stages of its design, the circuit breaker referred to in the paper and also of watching some of the tests. The design seems to me to be fundamentally quite sound. The authors appear to have been able to prove by tests that a single-break circuit breaker can be made which will do its work successfully.

I think there is no doubt that the development of the cross-jet pot has made the single-break circuit breaker possible. It certainly appears to be the most important feature of the switch, and to attack an arc from the side and so introduce a barrier to prevent restriking is fundamentally sounder than to depend on merely drawing the arc out.

Do the authors attach much importance to exactly simultaneous make and break? Personally, I do not think this matters much. Perhaps they would give some information about their operating mechanism. The fixed contact is a part which I have often heard criticized, but I see no reason why it should not be thoroughly sound from a mechanical point of view. I should like the authors to tell us whether they use a line contact or a surface contact.

Their single-break switch appears to have many features which should commend it to station engineers. The facilities for separating the phases are extremely good; also the facilities for separating one set of busbars from another are vastly superior to what we get with any of the more normal types of metalclad gear. In nearly all the ordinary designs the busbars are placed in chambers almost touching one another, and a fault inside a chamber will frequently cause the chamber to fracture. The design shown in Fig. 20 has a disadvantage in this respect as compared with the one shown in Fig. 21, where there is the possibility of a division wall between the main busbar and the reserve busbar (I think this is a better name than "auxiliary busbar"). In this respect my argument is borne out by what happened recently in one of the big American stations. There was entire phase separation, but the main and auxiliary busbars of the same phase were installed in a common chamber, with disastrous results.

The authors' circuit breaker is a step towards the ideal of the reduction, if not the elimination, of oil from switchgear equipments. Bushings are a weakness in switchgear, and I suggest that the authors' design would be improved if some of the bushings could be eliminated.

The cubic content of a building designed to house the gear described in the paper is substantially less than that required for any other type of gear, and therefore less expense is involved in keeping the building at a reasonable temperature in order to prevent the mechanism from rusting and becoming either sluggish or failing to operate due to the cold oil. Sufficient importance is not always given to the maintenance of a dry atmosphere in high-voltage switchrooms.

The ratings which switchgear makers have ascribed to their switches in the past appear to have been extremely optimistic, and I think they will find that purchasers of large gear will in future be more insistent upon tests, to substantiate the ratings.

In view of the fact that the switchgear described by the authors is much smaller in size than other metalclad gear, will it be sold for approximately half the cost? I would remind them that many successful businesses in this country (particularly electricity supply concerns) work on the principle of a small profit per article.

Mr. H. Pearce: In Fig. 17 the authors have plotted the arc lengths recorded in all the numerous tests they have made on their breaker, and have ignored any small changes in design there may have been since the original conception of the breaker. Fig. 17 shows that, in spite of such small differences, there is a definite relationship between the arc length and the current that is ruptured. The authors have drawn in Fig. 17 a line which is substantially straight over the greater part of its length, and practically parallel to a zone including the bulk of the tests. It seems reasonable, therefore, to assume that a line parallel to this indicates a general relationship between the arc length and the current throughout the range of those different conditions. This relation between current and arc length may be expressed by saying that for every sixfold increase in current the arc length is reduced by approximately 0·5 in.

In order to ascertain the average effect of voltage on arc length, I have taken the results given in Tables 5 to 8 and adjusted the arc lengths according to the above relation to compensate for the different currents. Taking the values separately for each voltage group, the results are shown by the points in Fig. N. Each point is the average value obtained from the number of tests indicated in the adjacent circle. It is clear, therefore, that the average effect of voltage on arc length lies somewhere within the zone embracing these points. The maximum effect is represented by the line marked "lower limit," which shows an increase in arc length of 1 in. for every 17 kV; while the minimum effect is indicated by the line marked "weighted mean," which shows an increase of only 1 in. for every 35 kV. The latter is more likely to be correct, as it takes into account the number of tests on which each average value is based. This graphical analysis helps to show why synthetic tests have proved a practical method of investigation when other facilities have not been available.

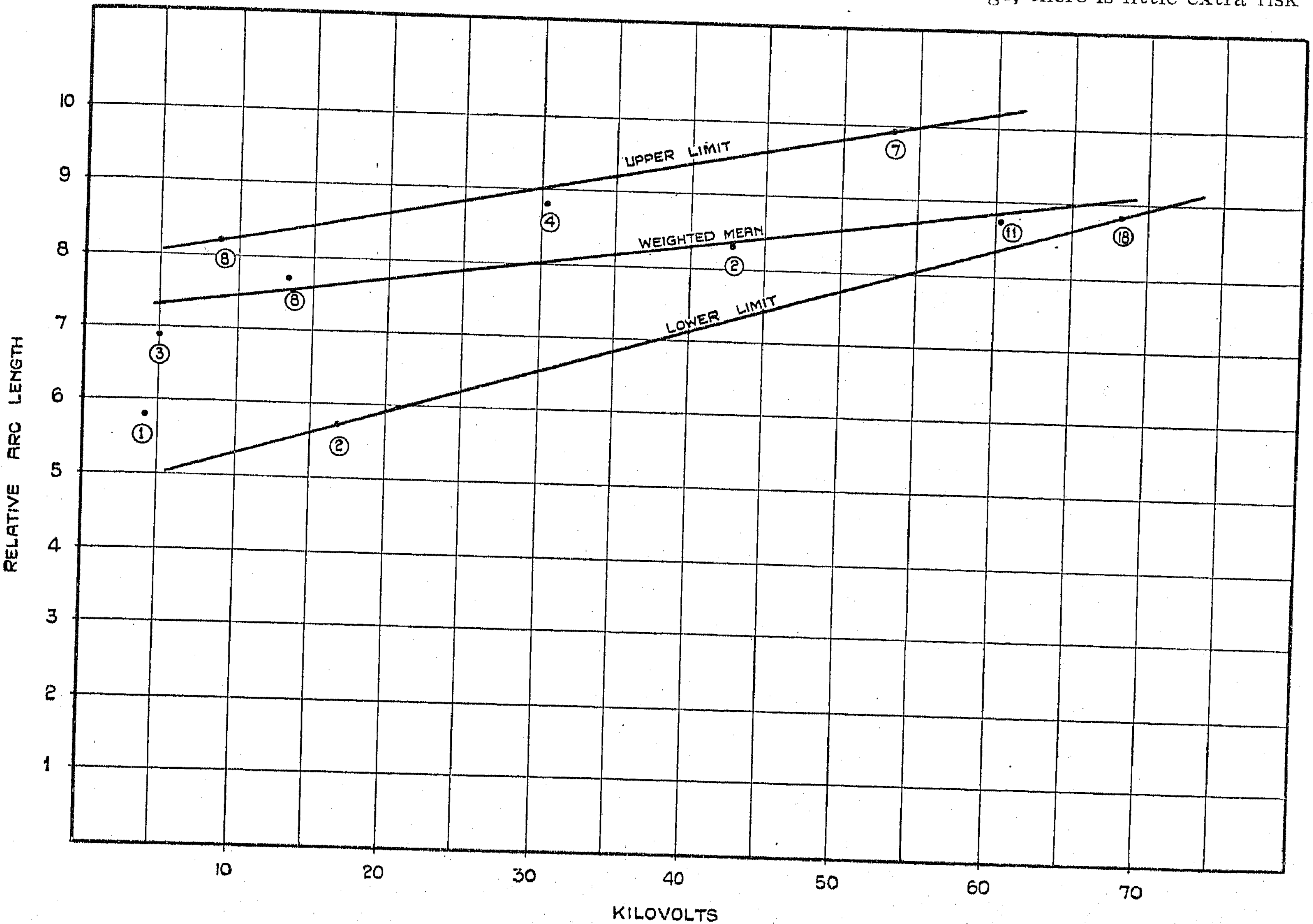

Fig. N.—Relation between average arc length and voltage, when current is constant.
Points ● represent values taken from Tables 5-8 of the paper, adjusted to compensate for varying current. Each point is the average value of the number of tests marked within the circle, thus:—③.

Mr. S. Ferguson: Some four years ago, when discussing the paper by Messrs. Pearce and Evans,* I remarked that the most important part of the paper was that which dealt with the cross-jet explosion pot. I am pleased that the development of this apparatus has been so successful and the performance so efficient that it has been found possible to rupture heavy powers on 66 kV with one pot only per phase. Although I believe space limitations were a factor in accelerating this innovation, the tests have fully justified it and it has an application for the future.

With properly designed cross-jet pots tested extensively over the whole range, there is little extra risk involved in relying on one pot per phase, as many of the causes of failure, e.g. welding-in on reclosures, mechanical damage preventing opening, etc., would render both pots inoperative. No defects in the pots themselves are likely to develop if they have been properly tested and the maximum pressures recorded, a factor of safety of 3 to 4 being possible.

Accepting the case as being proven, the important points to be decided are (1) the range of application, (2) the form of single-break breaker, and (3) the form of metalclad unit in which it is to be incorporated.

As regards (1), I think the authors have gone too low in commencing at 22 kV. The present designs are entirely satisfactory, and no material reduction in space can be shown for equipments up to 33 kV and 750 MVA, providing the breaker with three phases in a single tank is incorporated. In a 32-in. diameter tank with double cross-jet pots we have been able to rupture at least 800 MVA, and in a 36-in. tank over 1 000 MVA. The minimum diameter of a 33-kV single-break switch would be, say, 14 in., so that the width of the three tanks when touching would be 3 ft. 6 in. Thus there does not appear to be any economy in space up to 33 kV, 750 MVA. The justification and economy in space seems to come where complete phase separation in separate enclosures is demanded, i.e. at 33 kV for 1 000 MVA and 1 500 MVA, and at 66 kV for all rupturing capacities. It must not be lost sight of that a reasonable limit for the rose and candle-stick contact shown in the paper is about 1 200 amperes, which makes the simple design unsuitable for lower-voltage systems.

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* *Journal I.E.E.*, 1932, vol. 71, p. 703.

As regards (2), the form of single-break breaker, the horizontal type seems to possess decided advantages over the vertical type on the following grounds: (*a*) The terminals can be brought out at either the top or the bottom, rendering the breaker suitable for either outdoor or indoor installation. (*b*) There is no tendency to reclose by gravity in the event of the operating mechanism fracturing. (*c*) Visual inspection of contacts is facilitated, as it is not necessary to drain the oil but merely to remove the top cover. Furthermore, the joint to be broken has not necessarily to be oil-tight, as is imperative in the case of the vertical design.

Turning to (3), the form of metalclad unit, I doubt whether supply engineers would agree with the authors in adopting breakers which are non-removable. There is always the possibility of oil leakage and, in the event of failure through any cause, distortion of the container. I think the design must be such that the breaker can be removed bodily from the rest of the unit, and, furthermore, without shutting down the busbars. I doubt also whether operators would be satisfied with inspection windows for showing the earth position of the isolators. What type of unit, then, will be the future standard? Will it be: (*a*) a non-removable breaker and oil isolators; (*b*) a removable breaker and oil isolators, the breaker being handled by crane, but with no provision on the unit for supporting it in the isolated position; or (*c*) a removable breaker with all the facilities of the existing metalclad switchgear? Operating engineers have been so accustomed to this latter facility that it is unlikely that they will be satisfied with anything less. Whether this attitude will be modified on 66-kV gear, where the difficulties are so much greater, remains to be seen.

When the costs of single-break switchgear are under consideration it should not be lost sight of that there are the same number of incoming and outgoing bushings and the same number of main contacts as in double-break gear. What is actually saved is one cross-jet pot, and I believe the practice will be to make the remaining one bigger and with a higher factor of safety. The main saving on the larger units, if existing facilities are to be retained, lies in the smaller space occupied and in the reduction of oil volume, which are important considerations.

Mr. S. R. Mellonie: The term "leakage current" occurs many times in the paper, and it is rather confusing at first sight because the term is already in use with more than one meaning. Perhaps the authors would add a definition of this term when their paper appears in the *Journal*.

The double-break circuit breaker shown in Fig. 6 is fitted with arc-control devices; in view of the advent of these large pieces of insulating material, has not the time come to see that the material is taken right across and that the contacts are braced together? The only possible objection is the provision of a horizontal insulating surface, which would, of course, collect carbon particles; but the section would be designed with a view to eliminating this possibility.

With regard to the very interesting designs shown in Figs. 11 and 21, I should like to inquire whether the authors have ever been asked to provide facilities for earthing the feeder via the breaker.

There is a point on page 138 which I do not understand. Does not the statement "In extreme cases it is even possible for the voltage across one gap of a multi-gap breaker to exceed the entire restriking peak voltage across the whole breaker" imply that the part is greater than the whole?

We have heard a good deal about the possibility of trouble with the sliding contact; perhaps an unfortunate experience of mine in the last 12 months will be of interest to those who may be called upon to maintain this class of gear. The circuit breaker was one which embodied the very common construction of a sliding bush on a vertical rod. This breaker, for reasons of economy, was not opened for some months, and when the time came for inspection it would not open. Upon investigation it was found there was a growth on the steel rod sufficiently hard to lock the breaker in position. A satisfactory explanation has not yet been obtained. The fact that such conditions have occurred emphasizes the need of systematic operation in the course of maintenance work.

Mr. T. T. Evans: There is no doubt that the development of the cross-jet pot, and its efficient operation, engendered the idea that possibly one break could do the same work as two. A sample single-break breaker was therefore made, and was tested on every plant available. It was sent over to Germany, and was also tested in this country with the highest currents and the highest voltages we could put on it, and the results were remarkably good.

It was only the development of finer instruments that made such investigations possible. The magnetic oscillograph, for instance, has enabled a series of no less than 16 recordings to be made on one chart, and without the development and application of the cathode-ray oscillograph the results given in the paper would not have been possible.

In Fig. 3 and Table 2 the authors refer to test No. 6, in which the break nearest the fault is shown opposing the action of the second break to the extent of increasing the duty across it by 50 per cent, i.e. the restriking voltage across one break is shown to be actually considerably greater than that across the whole breaker. The restriking voltage therefore differs considerably from the theoretical value predicted, and I should like to ask the authors whether they have any explanation for this discrepancy.

Mr. A. C. Ehrenberg: The subject matter of the paper recalls to my mind very early experiments on a single-break circuit breaker which proved that in circuit-breaker design straightforward reasoning does not always yield straightforward results. A standard plain-break double-break circuit breaker of a nominal rating of 150 MVA was converted in the simplest possible manner into a single-break-per-phase circuit breaker by pivoting one side of the moving bridge in a manner employed in isolating switches. The argument put forward in favour of this device was, roughly, the following: The total arc energy appears to be the cause of mechanical failure of a circuit-breaker structure, and the reduction of this energy could most readily be achieved by reducing the total arc length. On grounds which the authors have outlined in their paper, it was assumed that the total arc length in the single-break breaker should not be more than about 60 to 70 per cent of the total arc length in the double-break form. Other considerations suggested that the arc duration would not be increased in consequence of a reduction in arc energy.

When actual tests were made, the surprising fact emerged that the total nominal arc length was only 30 to 40 per cent of that of the double-break construction; the arc duration was one-half, but the total arc energy was slightly more than for the double break and the tank pressures were correspondingly of the same order. The main reason for this surprising result appears to lie in the fact that the nominal arc length and the actual arc length in a plain-break circuit breaker are not always the same thing. The adoption of some form of arc-control device, therefore, seemed to be strongly indicated, and the authors, in their single-break circuit breakers, have adopted a form of arc-control device which has been proved very successfully on standard double-break designs and, as their test results show, also on single-break circuit breakers.

The single-break circuit breaker introduces the sliding contact as a comparatively novel feature in circuit-breaker design. Considerable experience with heavy-current contacting has eliminated from my mind any fear regarding the behaviour of this type of contact. While the design of such contacts certainly requires very careful scrutiny of every component part, practice has shown that designers of single-break breakers are masters of the problem. On the Continent, sliding contacts have been incorporated in nearly all the latest developments in circuit-breaker design.

Mr. S. Farrer: The authors mention space-charge effect as a factor which may possibly modify the rate of rise of recovery voltage in the testing circuit. It would be interesting to have a more detailed description of this phenomenon and to know whether in test No. 6 (on a double-break cross-jet pot), in which there was appreciable residual charge on the moving contact, the data were taken with the high-capacitance test-plant voltage divider in parallel with the moving contact-bar and earth. If so, would not the effect of this capacitance modify considerably the voltage induced by the space charge?

On examining the arc length in inches and the time in half-cycles for the various series of tests, the speeds are seen to vary from 10 to 25 ft. per sec. Some of the tests given in Table 6 for test plant B show speeds during arcing of approximately 11 ft. per sec. for 10 000 amps., whilst for the same current for test plant D (Table 8) the speeds are of the order of 17 to 18 ft. per sec., with a maximum of some 25 ft. per sec. I should be glad to know the cause of these apparent differences in speed, because the current broken appears to be the same and the arc lengths are also comparable, a fact which seems strange in view of the difference in the voltage of the respective tests.

In cases where the full rupturing-capacity rating of a breaker exceeds the short-circuit capacity of the test plant, a synthetic form of test such as that mentioned by the authors is generally adopted. As a general rule, however, with cross-jet explosion pots, it may be taken that the arc lengths tend to be slightly shorter at the lower voltages at full rated short-circuit current than at the maximum test currents available on full-voltage shots. The authors mention a figure of 4 000 MVA obtained by multiplying maximum voltage and maximum current in separate tests. I would suggest that a more conservative method should be used to assess the maximum probable performance or factor of safety of the cross-jet pot on the basis of the synthetic-test data. The adjustment is necessary owing to the fact that the full current at low voltage normally produces pressure inside the pot for a shorter period of time.

Instead of multiplying the full voltage by a maximum current obtained in a test at a lower voltage than the breaker voltage rating, I would suggest multiplying this current by a reduction factor determined from the ratio of the arc lengths and times in the two series of tests. This would be equivalent to making the assumption that had the test been carried out at full voltage of the breaker and at the full current of its short-circuit rating the arc would have been drawn out to the same length as on the highest currents for which full-voltage tests were possible; the pot performance based on synthetic-test data would then err on the conservative side.

The quantitative data given for the voltage distribution are of particular interest, but I would have preferred the authors to have laid rather more emphasis on the fact that this consideration referred only to the moments of zero, or nearly zero, arc current. The capacitance distribution which has been described occurs only at the period when the arc current is passing through zero value, which is the time when the breaker is trying to build up electric strength across its gap at a rate greater than the rate of rise of voltage in the testing circuit.

Mr. C. Dannatt: The authors' method of estimating and also measuring the voltage distribution across the breaks in series is undoubtedly correct, but the significance they place on the voltage distribution leaves me in some doubt. To illustrate what I mean, suppose one had a plain break in series with a cross-jet break, and suppose the capacitances of the breaker were so arranged that in the static condition the major proportion of the voltage appeared across the plain breaker; the authors would surely not argue from this that the plain breaker did most of the work in opening the circuit. In this connection Kesselring and Slepian have both shown that in an arc space the recovery of the electric strength begins to occur over a considerable period—for many microseconds, in fact—before the current zero. In other words, the process of arc rupture is well on the way, whilst the voltage distribution is still determined by the leakage across the switch. I would therefore suggest that the mere criterion of supposing the division of duty between two breaks to be the same as that given by the static voltage distribution is not necessarily correct.

Mr. A. C. Main: A feature of the single-break oil switch which is worthy of comment is the apparently extravagant factor of safety in the mechanical design of the switch cylinder. During manufacture, the 66-kV design is submitted to a routine sustained pressure test of 400 lb. per sq. in. The maximum shown in any of the oscillograms in the paper, however, does not appear to exceed 25 per cent of this figure as an instantaneous value.

Operation	Elapsed interval
	minutes
(*a*) Lower the oil level in the three tanks below door level, during which time all but two bolts per cover were removed	25
(*b*) Run off balance of the oil and remove the three door-linings, and the three cross-jet pots	13
(*c*) Remove the three main contact sockets and replace with spares	26
(*d*) Replace three spare cross-jet pots and three door-linings	15
(*e*) Wash door-faces and gaskets with benzine, re-grease gaskets, and bolt up the three doors ready for oil filling ..	27
(*f*) Refill the three tanks (estimated only in view of varying conditions in service)	25
Total time	131

There are some notable features in the mechanical construction of this oil circuit-breaker equipment which centre round the manner in which the designers have employed, and are dependent on, a sound technique in welded-steel construction. From this point of view the cylinders, isolating chambers, and mechanism parts, are worth examination in detail, and it is clear that the designers would find it difficult to produce a successful construction in the space in any other way. The entire absence of trouble with the sliding contact during construction and testing is also worth comment.

It is an interesting matter of electrical engineering history that, in the wider sense, the development of the gas-filled cable and of the single-break oil circuit-breaker have been coincident. I invite the authors to comment on the future possibilities for 132-kV indoor installations.

(*Communciated*) Since the reading of the paper in Manchester, frequent reference has been made to the question of accessibility of the main contacts for maintenance work. It will be a matter of general interest, therefore, to quote figures (see col. 1) in connection with a 66-kV switch unit similar to those illustrated in the paper. These figures represent no more than normal conditions and working speeds.

The oil discharge pipe, of 2 in. internal diameter, was connected to a 24-ft. length of flexible piping of 1½ in. internal diameter. Two men were employed for the test, although it is possible to carry out all the operations with one man, or, alternatively, three men can work in parallel during a proportion of the time if so desired.

For item (*f*) it is assumed that sufficient clean oil is held in readiness in a separate tank, this tank receiving oil from the oil-purifying plant. The total quantity of oil required for the three switch tanks is 360 gallons. Using three men the total time would be reduced to 105 minutes. To both periods an allowance of 10 minutes might be added for replacing the arcing tips and washing down the tank linings.

Mr. W. Symes: The title of the paper is rather a misnomer, as no reference is made to many parts of the development process such as drawings and designs, patterns and tools, special manufacturing equipment, and the provision of costly testing equipment and personnel. The oscillograms included in the paper are the product of years of work in the design, building, and operation, of testing equipment.

The authors have achieved a practical aim of producing a breaker with a greater margin of operating safety, including the factors of better arc control, lower pressures, and greatly reduced quantities of oil. Even if, as may possibly be the case, the single-break switch is more expensive than a double-break switch of equivalent rating, the authors have succeeded in making lower overall installation costs possible. The development of the single-break switch can therefore be considered a valuable contribution to switchgear design and operation.

Such advances would not be possible if the large development costs involved could not be recovered in a reasonable time. The solution to the problem is not, as Mr. Kidd suggests, for switchgear manufacturers to be content with low profits per unit. Their difficulty is how to make any profits at all, faced as they are continually by the problem of the recovery of development costs incurred by work of the nature described in this paper.

Mr. J. Solomon (*communicated*): Referring to Fig. 18, the oil volumes in the tanks for the three designs of 66-kV oil circuit-breakers illustrated are in the approximate ratio of 3 : 2 : 1. This substantiates the claim made for reduction in oil volume in the case of the single-break oil circuit-breaker, but it would be interesting to have similar ratios for complete 3-phase units and corresponding figures for 33-kV designs.

[The authors' reply to this discussion will be found on page 171.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 9TH MARCH, 1936

Dr. C. C. Garrard: I rather think the authors have made a virtue of necessity. They set out to design a type of switchgear which would take up less space, and not to produce a satisfactory single-break design; they hit upon the single-break design described in the paper, which, as they have shown, does everything that they claim for it.

The question arises: Why do people buy switchgear at all? The main consideration is that of insurance. It seems to me that a circuit breaker having two breaks is a better insurance than one having a single break. This applies especially to a circuit breaker embodying an arc-control device, because such a device has a rather peculiar characteristic; that is to say, it functions extraordinarily well over a certain range and then suddenly fails entirely. A plain-break circuit-breaker does not do that; it is more gradual. If a curve be plotted of the current broken against the efficiency of the breaker, the arc-control device seems to produce a very sharp knee in the curve. Therefore, bearing this in mind, a 2-break device must have a larger margin of safety, because one of the devices could fail and yet the other one be available. I am, of course, not arguing against the arc-control device as such, because a device of this sort is necessary if one is to obtain short arcing times.

In this connection Table 4 requires a little explanation. From the bottom line of figures it appears as if there is very little difference between the double break and the single break; nevertheless, the volt-ampere rating of the single-break circuit breaker is 77 per cent and the arcing time 111 per cent, as compared with the double-break type.

With reference to Table 5, I do not quite agree with the remarks with regard to test No. 13, because it seems a weakness to exclude certain conditions as being impossible in practice. I think that circuit breakers should deal with any kind of current within their rating. In Fig. 16, the tail of the curve turns up, whereas in Fig. 17 it does not do so. Why is there this difference? I should like to ask, with regard to these curves, whether the recovery voltage was corrected for power factor and d.c. component.

The "synthetic test" dealt with on page 142 is very interesting. Do the authors really claim any validity for such a test? On the basis of the synthetic test they claim a breaking capacity of 4 000 MVA, which of course would correspond to a making current approaching 90 000 amperes (peak), a current much larger than any mentioned in the paper. All this brings out one of the most important questions in connection with circuit-breaker testing at the present moment, namely: Is the rate of rise of restriking voltage the true criterion of test? Are the authors of the opinion that the inherent severity of a testing station, for example, can be settled upon the basis of the natural frequency of oscillation in that station?

Regarding the circuit-breaker designs shown in the paper, it seems that in Fig. 19 the authors have not the courage of their convictions, since they have not taken advantage of the small phase centres which their design provides. I do not believe in compressing switchgear into the minimum possible space, however, because if anything happens to go wrong with one item the whole is likely to be involved. I should like to comment on a detail of the design shown in Fig. 20. The authors have been very careful to round all corners, etc., except those of the busbars. Again, these busbars are compound-filled, as are various cross-connections, and yet the gear is put forward as an outdoor type. I do not think compound is suitable for outdoor-type gear. In some quarters lately the idea has been put forward that oil should be entirely avoided; this, I submit, is going too far. For instance, there can be no doubt that an oil-immersed transformer is much safer than an air-blast transformer, from the fire-risk point of view. Oil, if correctly applied, makes for safety, and its abolition would not necessarily be to the general advantage.

Mr. K. J. R. Wilkinson: I think the paper demonstrates clearly that for circuit breakers which are not of the plain-break type, but in which control of the arc is obtained, for example, by a cross-jet of oil, the single break can be electrically adequate and has mechanical advantages.

It is necessary, however, to bear in mind the increased potentiality possessed by the controlled-arc breaker for producing voltage-surges in the system. Thus Figs. 4 and 5 show the restriking voltage for an 11-kV cross-jet breaker as quite free from the post-arc conductivity evident for the same breaker at a similar load without cross-jet pots, and in this instance the cross-jet breaker involves the system in approximately twice the surge voltage of the plain-arc breaker. While such a voltage is neither excessive nor dangerous, attention should be directed to those load conditions where it is possible for the controlled-arc breaker to cause appreciable current suppression. Thus in Fig. 9, which applies to a cross-jet 33-kV breaker on relatively light current, the initial "negative" restriking voltage is to be taken as evidence of pre-zero-current suppression, the effect of which is not only to increase the amplitude of the restriking voltage by an amount proportional to the "negative" loop, but, more important, to distort the form of the restriking voltage in such a manner that a greater proportion of it tends to appear across those series impedances which form part of the system adjacent to the switch; for example, as inter-turn or intersection voltages in the case of a transformer or reactor winding. It would seem that the upper limit of such voltages is set only by the rate at which insulation strength is built up by the switch during its action of suppressing the arc, and it would be paradoxical if a circuit-interrupting device should, as a result of its excessive efficiency, cause damage to the system it was designed to protect.

Mr. H. T. Stratton: Dealing first with the subject of speed of break, on page 135 the arc duration in one of the tests with a plain-break breaker is given as 15·7 half-cycles. For a commercial breaker with the usual speed of break, dealing with the voltage and current stated, it would appear that a length of break of approximately 11 in. per contact would be required, and I do not know of a maker who supplies breakers with anything like this arc length. No doubt the authors can enlighten me by stating the speed of break of the particular breaker, and the power factor at which these tests were carried out.

On page 138 it is stated that the tests were taken up to 82 000 (peak) amperes and 29 400 (r.m.s.) amperes at interruption. I assume that the figure of 82 000 amperes refers to the peak value of the asymmetrical wave with an r.m.s. current of 29 400 amperes; this point is an important consideration in determining the making capacity of a breaker. If the power factor is as low as 0·1, the figure of 82 000 amperes appears to be a little on the high side.

Referring to the remarks on page 144, under "Maintenance," are the arrangements such that the feeders are earthed through the closed breakers; and can these be locked in?

It has been mentioned that the single-break switch has an advantage over the double-break type owing to the absence of the magnetic loop experienced with the introduction of the cross-bar, the corresponding forces tending to open the breaker on closing being therefore considerably reduced. With the high voltages mentioned in the paper, however, I doubt whether these forces are anything like those encountered on low-tension heavy-current gear, and I consider that they would not substantially affect the design of the closing mechanism.

Mr. J. H. Patterson: It seems that to-day engineers do not realize that a low-priced circuit breaker may be of inferior quality. They do not realize that far more money than is necessary is spent on switchgear maintenance. The primary aim of the electric supply industry is to give continuity of supply to all consumers. One often hears the remark "One cannot depend upon electricity; I would rather have gas." That is partly true, and it is so because certain factors in oil-switch design are not sufficiently well understood. The troubles met with in practice are not always due to breakdown of the oil-switch contacts; I have had experience of breakdowns caused by flashing across the top of the pots due to insufficient clearance, ionized air, or lack of ventilation —all remote from the oil switch itself. I am of the opinion that ample clearance should be given at this juncture, until more investigation has been made and a robust mechanism is put on the market which is entirely safe with smaller clearances, enabling transients, at present not reproduced under test conditions, to be present without causing damage to the unit.

Mr. H. S. Davidson: It is somewhat disappointing to me to find that the experts are not all in complete agreement with the authors, because from the point of view of maintenance their designs represent a great step forward.

If one considers the present arrangement of 132-kV circuit breakers such as are used by the Central Electricity Board, one finds that each phase occupies a tank containing roughly 1 000 gallons of oil. These circuit breakers have, in some cases, four breaks per phase. To carry out maintenance work on such circuit breakers involves the drawing-off of the large quantity of oil mentioned, the opening-up of manhole covers (after a temporary shelter has been erected to guard against unfavourable weather conditions), and the aeration of the tank to permit the entry of a workman. There are then some 16 arcing contact-fingers and 32 main contact-fingers which may or may not require attention. Comparing this type of circuit breaker with some of the designs suggested by the authors, it must be apparent that if the latter are sound from a technical point of view then enormous progress has been made towards easier maintenance.

The space factor is important too, because of the increasing difficulties in obtaining substation sites in industrial areas. One can visualize the time when substations will occupy much less space than at present, if the authors' designs are generally adopted, although in the case of outdoor substations the clearances required between bare conductors may be the limiting feature preventing full advantage being taken of switchgear occupying a smaller amount of space.

I should like to know how far the designs shown have been put into commercial operation, and particularly to what extent they have been developed for voltages of 132 kV. The oil-tank arrangements shown in some of the designs would be improved if provision were made for two tanks, one into which dirty oil could be drawn off and a second containing clean oil for refilling. Finally, it would be of interest to have some details of costs.

Mr. C. J. O. Garrard: There is one aspect of the development of metalclad switchgear such as that described in this paper, which appears to warrant careful attention. This is the importance of reducing as far as possible the number of oil-tight joints used in assembling the components of the gear. If we take the 3-phase breaker illustrated in Fig. 11, there are, including the busbar chambers belonging to the unit and excluding the cable sealing-boxes, 12 separate chambers containing oil or some other more or less liquid, inflammable substance; 15 condenser bushings; and not less than 48 main oil-tight joints, besides those belonging to the oil supply and drainage piping.

I do not raise the point in order to compare to its disadvantage the single-break circuit breaker with any other type of oil-insulated metalclad gear, as in respect of multiplicity of chambers and joints they are all very similar, but rather to put the question whether a development which leads to a switchgear installation resembling in some degree an oil refinery is really sound.

Mr. W. A. Coates: One of the points which the authors do not stress in the paper, but which has meant a lot in their experimental switch, is the fact that they have contrived an explosion pot in which there is no metal whatever beyond the level of the main contacts, as is seen in Fig. 12. It has been found in practice that where explosion pots are built up with insulated steel or bronze housings gas is liable to get behind the lining and cause a breakdown, or a puncture right through the throat material. There is very little doubt that the all-insulated explosion pot is the only safe construction.

The arrangement shown in Fig. 11 can be effectively made fireproof very easily, while still remaining of very small dimensions. The cable box can be completely walled in. The busbars are condenser bushings, made of solid bakelized paper with an earth band on the outside. They can therefore be built into a wall, so that there is no communication of oil channels from the one section to the other.

After a circuit breaker has operated on short-circuit, it is necessary to inspect and clean the contacts. The arrangement shown in Fig. 11 has 18 bolts on each tank door; taking a similar double-break switch there are 20 bolts to be undone. These 20 bolts, moreover, are in a horizontal plane and may be hidden by mechanism. In this single-break design there are 130 gallons of oil per phase, and in the other 430 gallons, i.e. 300 gallons of oil less to be handled. In the single-break switch, oil is emptied by opening a valve; in the other case the whole tank must be lowered, and as the oil with its containing tank weighs 3½ tons emptying takes a considerable time. Finally, when the breaker is put back the oil must be filtered. With any ordinary filtering equipment the difference in filtering time amounts to about 3 hours.

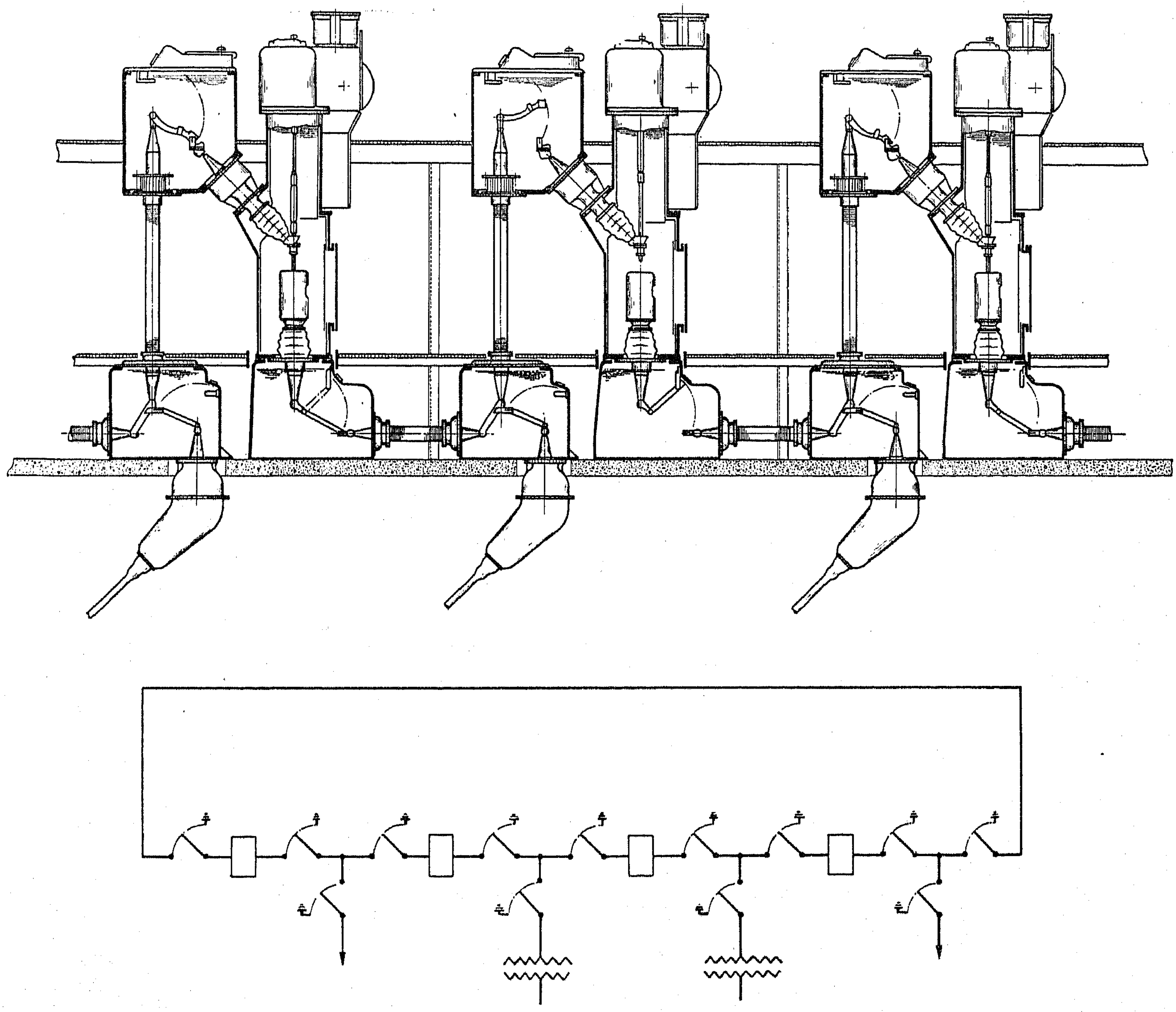

Fig. O

Those engineers who are familiar with the grid system will doubtless be acquainted with what is called the "mesh connection." This arrangement of busbars is good, firstly because it saves one circuit breaker per equipment as compared with any equivalent system of connections, and secondly because one circuit breaker can be taken out of service for maintenance while every circuit in the station remains alive. The arrangement shown in Fig. O compares with the 132-kV layout in Fig. 19, and shows the way in which single-break gear could be connected up for "mesh" connection while preserving all its own special features.

[The remainder of Mr. Coates's remarks was similar to his contribution to the London discussion (see page 154).]

Mr. D. Kingsbury: Switchgear is expensive because switchgear testing plants are relatively new to the industry. The plants in this country have probably cost half a million sterling, and as a result of these plants considerable research work is being undertaken and experimental models are being made in order that ultimately switchgear shall cost less, in first cost, in maintenance, and in consequential cost due to failures.

Turning to technical points, although one often hears the use of oil in circuit breakers criticized, it appears to be very suitable for this particular service. We know that hydrogen is a very good de-ionizing agent, and in oil we have a stable liquid with high insulating properties which only requires an electric arc to liberate gases of which hydrogen forms about 70 per cent. Air-blast breakers which require the maintenance of compressed air, and expansion breakers which require the maintenance of water in a fairly high state of purity, have been offered, but I think time will show that they cannot supersede the oil breakers. The authors are responsible for an important development in that less oil is being used in their circuit breakers than in other types. The less oil there is about any given plant, providing there is sufficient, the better.

In the first examples of some of the explosion-pot designs there was a critical fault current at which the arc was liable to get right outside the pot, making a second line of defence imperative. This value was generally in the region of 10 to 15 per cent of full rating. It may be that as time goes on we shall feel so sure of the performance of these pots that a second line will not even be thought of. The more conservative engineers still like the second line of defence, i.e. an adequate break after the moving contact has left the pot.

It is to be hoped that the importance of the rate of rise of recovery voltage has been settled, because our confidence will be seriously shaken if someone shows that it is not a criterion of severity. It is to be hoped that before long a statement of the maximum short-circuit kVA which impedance figures show can occur at a given point on a network, together with a statement as to the maximum rate of rise of recovery voltage at that point, will enable a manufacturer to put forward a circuit breaker which can be guaranteed to do its duty adequately without being extravagantly designed.

I cannot agree with the authors that the amount of deterioration of the oil in a circuit-breaker tank is a function of the number of contacts; I think it is a function of the design of the breaker. It is a fact that explosion pots produce a most remarkable reduction in the carbonization of the oil, but I do not think that two explosion pots in series do twice as much damage as one, any more than six plain breaks do six times as much damage as a pair of breaks. Surely the carbonization is a function of the watt-seconds of arc energy, which in turn depend upon the design of the contacts and not the number in series. There is a point too in the authors' design which is not clear to me from a preliminary inspection of the drawings, namely, that although it is easy to get inside the tank it does not seem easy to get at the fixed contacts. Mr. Coates makes the point that 18 bolts on a vertical face are used instead of 20 bolts on a horizontal face, as in the more usual types of gear, but that the number of bolts is no criterion if there is a considerable amount of work to be done round the back of the contacts after the front plate has been removed. In the present types it is easy to get all round the contacts, and I believe at least one design has a breach-block action whereby the explosion-pot assembly can be dropped, leaving the fixed contacts available instantly.

The circuit breaker is also a circuit maker, and there is a definite limit to the current that can be made on the throat type of fixed contact. There comes a point in the scale of making currents when one has to give away more in contact design to be able to put a pot around the contacts to improve breaking capacity than one can afford from the point of view of making capacity.

Finally, in regard to fire protection, it would appear that solid compound has definite advantages over oil as a means of insulation in trunking. The type of cable usually found connected to switchgear is capable of giving off fumes which render it impossible to get near to the seat of a fire. The greatest care should be taken to ensure that a relatively small mishap, liberating a certain amount of ignited oil, does not become a major accident due to flames from the oil coming in contact with cables. Again, one must consider the possibility of simultaneous earth faults on different phases causing heavy currents to flow in the sheaths of certain cables and in that way starting a cable fire, with its associated fumes.

Mr. R. Dean: Although I greatly appreciate the time and effort which are being put into research work to improve the performance of circuit breakers I feel that all such progress is but a means to an end, namely the provision of a reliable, abundant, and cheap supply of electricity; and that as far as the financial aspect is concerned circuit breakers are more backward than any other type of electrical equipment. In order to substantiate this statement I propose to give details in regard to cables and generating plant.

Table B

Rated volts	Approximate carrying capacity	Approximate price per yard	Approximate price per 100 kVA transmitted
	kVA	shillings	pence
400	200	10·0	60
6 600	3 600	11·25	3·75
11 000	6 000	12·75	2·55
33 000	16 000	31·5	2·36

Dealing first with cables, and considering a 3-core 0·25-sq. in. armoured cable, the figures in Table B may be quoted.

It will be seen that our cable makers are able to offer supply engineers, and indirectly the public, very appreciable savings if they will use higher-voltage cables capable of dealing with greatly increased quantities of power, and one cannot deny that considerable research has been necessary to bring the art of cable-making to its present high standard.

Referring now to generating plant, prior to the advent of the grid we were taught to believe that, by purchasing units of plant capable of considerably larger output, very material economies would be effected in initial cost per kW. These, I must admit, have not yet materialized in the case of turbines and alternators, as I believe that one can now buy 6 000-kW sets at a price per kW equal to, if not less than, that of 30 000- or 50 000-kW sets. I feel that such a position leaves much to be desired.

In the case of circuit breakers, however, the position is far worse. Complete metalclad circuit breakers with duplicate busbars, and having a rupturing capacity of 100 000–250 000 kVA, can be purchased at approximately 30s. per 1 000 kVA of rupturing capacity; but for breakers having rupturing capacities of 500 000–750 000 kVA and higher, the figure rises to £3 or £3 10s. per 1 000 kVA. It cannot be denied that, owing to the heavy cost of high-rupturing-capacity switchgear, supply engineers are being compelled to design system layouts in which the number of circuit breakers is reduced to even less than a desirable minimum. One appreciates the heavy cost of installing and operating a circuit-breaker testing plant, but unless such plants enable more efficient apparatus to be offered at prices which industry is prepared to pay, they are not fulfilling their purpose. I feel that the industry as a whole would be far better served if a national test plant were available under the control of an independent authority, such as the National Physical Laboratory.

Although the single-break design described in the paper is undoubtedly much simpler and smaller than double-break gear, and therefore less costly to manufacture, I understand from the discussion of the paper in London* that very little reduction in price is anticipated, the main saving claimed being in installation and building cost, due to the smaller bulk. In this connection I would point out that the authors do not give the dimensions of their breaker, and the addition of these when the paper is printed in the *Journal* would be appreciated.

From Fig. 19 it would appear that the top guide contact is carried by means of a long cantilever. This arrangement seems mechanically weak, and I should have preferred this contact to have been supported on a bridge piece. I noticed from the authors' slides that the isolator chambers are fitted with glass windows, in order that the operation or position of the isolating switches may be readily seen. This, I understand, is standard practice for this type of gear, and I am pleased that a feature so essential to added safety in operation and maintenance has been incorporated in the authors' design.

Turning to Fig. 5 (Plate 2), the first item of oscillogram (*b*) shows that with a current of only 58 amperes (r.m.s.) the arcing length was the full limit of travel of the switch, namely 17 in. This I do not consider satisfactory, as I cannot accept the explanation that such small values of current at very low lagging power factor are unlikely to occur in practice.

In conclusion, I wish to refer briefly to the method of supporting the main cables. These are invariably e.h.t. single-core lead-covered cables, with no armouring, and with the added weight of a large volume of paper. Such cables require particularly careful handling and installation, and call for a type of cleat which provides at least twice the bearing surface of the normal type of porcelain cleat, if damage to the lead sheath is to be avoided. Where standard-type cleats are used in which the width of the bearing surface is often only equal to the diameter of the cable, indentations are likely to occur on the surface of the lead, which obviously must upset the electric stresses in the cable dielectric at these points.

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, MANCHESTER, AND BIRMINGHAM

Messrs. D. R. Davies and **C. H. Flurscheim** (*in reply*): As in a number of instances speakers at different Centres have made generally similar comments, we have classified our reply to the various discussions under the main headings of the paper.

Theoretical Considerations

The second break of a double-break conventional unit fitted with interrupting devices has been described by Dr. Garrard and Mr. Blandford as affording a second line of defence in case of failure of the first. We have shown that under normal fault conditions the second contact contributes a negligible amount to the interrupting duty, both as regards resisting the restriking voltage oscillations and reducing the subsequent voltage gradient across the live-side gap. The question arises, should the live-side contact fail, upon which falls 85 per cent of the interrupting duty, will the second gap in reality act as this back-up protection? Failure of the first contact may be either dielectrical or mechanical. If the former occurs it is suggested that the second gap will take upon itself the whole restriking oscillation, and thereby bring about interruption. We have, however, made analyses of a large number of cathode-ray oscillograms showing the voltage distribution across two cross-jet contacts at current zeros, at which dielectric failure of one contact has occurred. In every instance simultaneous failure has occurred in the second contact within the limits of measurement of about 5 microsec., and no appreciable transference of duty has taken place. This immediate breakdown always occurs in the earth-side gap, although the stress across it, as measured by the rising restriking wave, is only a fraction of that which the line-side gap has withstood before failure. As it is to be expected that each contact will develop electric strength at an approximately equal rate, we attribute this phenomenon to voltage surges produced by the mechanism of dielectric collapse in the first gap to fail. An example of this action is shown on the right of Fig. 9. The line-side and earth-side cross-jet gaps have failed simultaneously with voltage stresses of 25 000 and 2 300 volts respectively. In Fig. 5, six such failures are shown for a plain breaker in which grading has occurred. Again no transference of duty has occurred, although it is possible that transference might occur with this inefficient type, for in this case breakdown is a gradual process requiring several microseconds and may not be accompanied by surging. Whatever the precise cause, the result is that the second gap does not provide the back-up protection that might otherwise be expected from it under conditions of failure of the first.

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* See page 151.

Should mechanical failure of one contact occur, the causes which can bring this about, such as excessive arc length or duration, are simultaneously common to the second contact, and it is probable that failure will occur there also. We believe, therefore, that no appreciable increase in safety is brought about by duplication. It is, in fact, fair to say that duplication of parts that cannot take a fair share in the operating cycle under any of the severest conditions, actually reduces the overall reliability.

Mr. Ratcliff questions whether the capacitance-controlled voltage ratio under test conditions holds in service. This must be exactly the same for similar types of fault, although the oscillating frequencies probably will not be as high as the highest used during our tests. We did, however, use a specially modified system connection for certain of the tests in which the frequencies would be comparable, and the same effects were observed (Tests Nos. 2 and 4, Table 2).

Mr. Clothier claims an improved ratio 75–25 per cent on a rotating-contact breaker, as against 85–15 for the longest arcs on the normal breaker we selected for our tests, this having been obtained by an arrangement which allows of constant clearance and capacitance between moving contact and earth. Since, as the breaker opens, the capacitance between fixed and moving contacts always initially falls very fast, the voltage ratio will fall to 75/25 in the first inch or two of travel, and will then remain fairly constant as the breaker continues to open, instead of falling off a further 10 per cent as in the conventional arrangement. It is, therefore, probable that the short arc duration of this 132-kV breaker at 100 per cent rating is to be attributed more to efficient contact design and to testing with insulated fault and earthed neutral (affording more favourable voltage distribution than the reverse method), than to any great internal improvement in voltage ratios.

Mr. Blandford suggests that the ratio of 85–15 is not representative for conventional breakers, but we would draw his attention to the 90–10 ratio referred to in the text and obtained by Dr. Slepian. Mr. Blandford also refers to voltage grading by means of the interrupting contacts, but gives no indication of how this is done. If he is referring to the standard " deion " contact, the metal plates in this structure will form small condensers, but as they are in series with one another there will be a negligible increase in capacitance between fixed and moving contacts. He considers that our divider capacitance appreciably distorted the true ratio, but the actual and slight change is shown in Fig. 7.

Mr. Adam is correct in stating that, with extremely short arc lengths, distribution across a two-break design becomes somewhat more balanced, but we see no prospect at present of obtaining consistently arc lengths of 1 in. over a range of current at 33 kV, and such a length becomes necessary to obtain any appreciable improvement. Should such lengths become attainable there would be no difference between the conventional and the rotating-arm arrangements, since large oil clearances between contact arm and tank would be maintained at interruption in both instances.

As regards the maximum voltage for a single-break design, the distribution theory holds to any limit, and since in the past it has been possible to construct two contact breakers of 132 kV and higher, one of these same contacts will do the work almost as well and, with modifications permissible in a single-break design, can be made to give an even better performance.

Mr. Clothier and Mr. Allan refer to a single plain-break metalclad breaker produced prior to that described in the paper. Their conversion of this design to multi-plain break with improved performance is in agreement with the theory we have advanced for this type of circuit breaker, in which leakage resistance grading probably occurs. The single-break metalclad breaker is not new, but what is new is a successful design of this type, which is partly due to an appreciation of the differences between plain-break and arc-control action in voltage grading.

The instrument initiated and designed by Messrs. Trencham and Wilkinson for restriking voltage-wave measurement should be of very real value, affording, as it does, the only practical available undistorted measure of inherent wave-form. Mr. Wilkinson has suggested that plain breakers are preferable because they suppress the high-frequency oscillations. This type cannot, however, be relied on to do this consistently, because, as mentioned in the paper, when occasional and fortuitous efficient interruption occurs the oscillations are no longer suppressed. Certain plain breakers at low voltage are also fairly consistently efficient, and these probably have no leakage current at all—and have no resistance grading. The cathode-ray films shown represent the case of inefficient plain-breaker operation, which has been one of the justifications for some multi-break designs in the past. The suppression of current before the true zero is at present inevitable with any efficient high-voltage breaker. The excess peaks are not, however, of a dangerous value, as is shown in the Appendix, and no trouble should be experienced from the wave deformation that may occur.

Dr. Whitney suggests that the tangential method of measurement of restriking voltage is not necessarily comprehensive when more than one frequency is present, and with this we agree, but the amplitude of the first high-frequency waves in Figs. 9 and 10 are in both cases greater than 80 per cent of the peak 50-cycle recovery voltages, and the tangents are, therefore, in conformity with the proposed American standards referred to by Mr. Coates.

We believe with Mr. Coates that of all those proposed the tangential method (OA in Fig. H) employed has the greatest significance. We have, however, also given the maximum peak voltages, the ratio of which will be the same as that for rates measured by the alternative method, neglecting the extra high-frequency components as given by his line OB (Fig. H), or by Dr. Whitney's OB (Fig. F). The correlation of the importance of these two factors, rate and peak, as discussed by Mr. Adam, is of considerable importance and is a subject on which as yet there is very little data available. The tangents have been drawn through the points of zero current, but where leakage currents occur these can obviously only be approximately located, as in Test 3 (*c*). For the other tests mentioned by Dr. Whitney, reasonably accurate location of the zero is possible on the negatives.

Mr. Evans and Mr. Mellonie have asked for an explanation of Fig. 3 (*d*), Test No. 6, in which the restriking voltage across one break was greater than that across the whole breaker. In the paper, in order to reduce theory to the minimum and to that for which we had experimental proof, we have based our arguments on the simplest case in which arc voltage is assumed negligible. In some of the tests this was not the case, and we should expect variations according to whether both arcs become sensibly infinite in resistance at the same instant, or at intervals separated by a few microseconds.

If the synchronization is exact, the voltage-changes across each gap will be proportional to the capacitance ratio, but the total voltages at the first peak will only be in the same ratio if the initial arc voltages are zero. If, for instance, we have an initial arc voltage at the commencement of interruption of — 5 000 volts across each gap, and a total change during the first high-frequency oscillation of + 20 000, with a capacitance ratio of 50 : 1, then only + 400 volts change will occur on the earth-side gap, which will remain with — 4 600 volts across it. This is what occurred in Test No. 6, and to some extent in Test No. 15, and it may cause the second break to be a definite liability.

If synchronization is not exact, the changes in voltages across the earth-side gap may be more or less than the theoretical, one of the arcs acting for a few microseconds as a high resistance. The distribution of restriking voltage may, therefore, be better or worse than predicted, although, as circuit breakers go, the total variation in the tests of Table No. 3 is not of much importance. Such as it is, it tends to make the variation in performance of a multi-break design greater and, therefore, more difficult to test satisfactorily as compared with the single break, as a larger number of tests are required to ensure the worst condition having occurred.

In reply to Mr. Mellonie, by leakage current we mean a small current-flow in the arc after the final zero of the short-circuit. This current is referred to in detail in References (2) and (3) on page 148.

The interesting case of an inefficient plain break in series with an efficient controlled arc break, raised by Mr. Dannatt, can be explained by the theory given in the paper. If the plain break is inefficient, at the time of current zero the dielectric resistance will still be low. The controlled arc break will, however, have a sensibly infinite resistance. Under these conditions the capacitance voltage control will be swamped by the resistance control, so that the efficient arc may perform all the duty even if on the earthed side of the breaker. The capacitance-controlled ratio will be gradually restored as the dielectric resistance in the plain-break gap builds up. This may actually commence during the first high-frequency oscillation, or may be delayed appreciably longer. Whether interruption should commence at or before the final current zero seems immaterial to the argument, since the commencement of interruption never presents any difficulty. At every zero, even with the shortest arcs, the restriking oscillation begins, but failure occurs when the voltage amplitude becomes too great for the electric strength of the gap.

In reply to Mr. Farrer, we would point out that the space-charge theory mentioned in the paper was put forward by Dr. Kopeliowitch as an explanation of why the voltage could be equally distributed across a multi-break unit. Our experiments (Series II) have confirmed our belief that this effect, if it exists at all (and it is difficult to isolate it from slight leakage current or lack of synchronization effects), is of a very small magnitude. It is true that in the Series I test no quantitative check on this could be obtained because of the large divider capacitance, but in Series II no appreciable masking of the phenomenon can have occurred.

The capacitance ratio of voltage division, as Mr. Farrer points out, naturally holds only during the periods when the breaker is attempting to interrupt subsequently to each current zero, and also throughout the final restriking and recovery voltage periods. The voltage distribution during power arcing is resistance-graded.

Thus each break is subjected to the full distress, while only one performs the interrupting duty.

Short-Circuit Tests

Messrs. Ratcliff, Blandford, and Kingsbury, have referred to arc energy as a criterion of distress. In practice it is found that considerable variations in arc energies occur even in consistent breakers under repeated similar tests, while the visible distress, tank pressure, and deterioration, are not closely related with these values. For the single-break 66-kV unit the 3-phase arc energies varied from 0·38 to 0·77 kW-sec. per MVA interrupted at 66 kV. Over a few tests made on a double-break equipment employing two contacts of duplicate design the range was 0·43 to 1·3 kW-sec. per MVA at the same voltage.

While we agree with Mr. Kingsbury that deterioration in a breaker is a function of contact design, with similar contacts arranged in series, it must also be a function of number of breaks, unless the arc durations are cut down very appreciably by the duplication, which we have shown is not the case.

The proposal to rate the breakers by current and voltage, rather than by kVA as advocated by Mr. Ratcliff, will, it is hoped, be gradually accepted by the industry since the product of two quantities measured at different instants of time has no real significance and causes a lack of uniformity in interpretation of test results. This change in rating has been suggested by the I.E.C. and is embodied in the Specification now under discussion before the various national Committees for acceptance.

A number of speakers have referred to the synthetic figure of 4 000 MVA suggested as the ultimate limit upon which the mechanical factor of safety of the breaker could fairly be based, and Mr. Harris in particular has asked us to define our ideas in regard to synthetic testing.

The practical considerations to be met in order to justify this method (as apart from those of finance) seem to us to be: (*a*) that the component parts of such a test should give similar arc lengths and durations, (*b*) that the breaker should perform consistently; (*c*) that if the breaker is of the self-generating arc-control type, the interrupting characteristic shall improve, or at any rate not deteriorate, with increase in current within the limits employed for a synthetically obtained rating; (*d*) that if the breaker is of the externally-applied fluid-blast type, the mechanical flow shall not be appreciably altered by increase in current up to the same limit; (*e*) that it should not be applied to the plain-break type; (*f*) that in deriving an ultimate figure on which to show a mechanical factor of safety, the maximum values of individual tests complying with (*a*) and (*b*) may be used; (*g*) that in deriving a rating, average values of two series of tests be used as suggested by Mr. Farrar, or a correction be applied to (*f*) for the average effect of voltage.

The figure we gave complied with all the relevant criteria given above. To derive a rating from Mr. Pearce's curve (Fig. N) the weighted mean correction factor for arc length for a range of 10 to 70 kV is 0·82, and, allowing for an increase in arc duration of a similar order, the corrected kVA would become $4\,000 \times 0{\cdot}82^2 = 2\,670$. That a factor of safety on figures derived in this manner as usually allowed does not seem to us to detract from their value, but rather is it in line with all normal engineering practice in which factors of uncertainty are employed based on fracture and elastic limits. What this factor should be will vary with the extent of extrapolation and with the performance of the breaker.

Replying to Mr. Clothier, if the tank pressures were 7 times the figure of 90 lb. per sq. in., obtained in a test at 600 MVA, no damage would be sustained by the tank structure of the single-break unit, which is capable of withstanding impulse pressures of about 1 000 lb. per sq. in.

Dr. Garrard is incorrect in his assumption that the breaker would not make the current corresponding to the above synthetic test, since, as shown in Table 6, Test 16, a make-break duty was actually carried out, the making peak having been 82 000 amps. In reply to Mr. Stratton, the high ratio between the above peak and the r.m.s. value of 28 400 amperes at the time of contact separation is due to the time interval and consequent generator decrement between these two instants, the breaker in this test having had delayed tripping in order to allow the mechanism to latch fully home.

The policy of fitting interrupting contacts to circuit breakers, as advocated by Messrs. Pearce and Evans in their paper* before the Institution 4 years ago, which policy received some opposition at the time, has now been generally accepted. We, however, advocate their use at lower voltages than does Mr. Clothier, who still prefers plain-break operation at 6·6 and 11 kV. We have not experienced the additional difficulty, referred to by Mr. Kingsbury and suggested by Mr. Stedman, in making very high peak currents with throated pots, any increase in throw-off force caused by pre-arcing gas pressures being offset in double-break units by the more favourable magnetic loop arrangement as compared with a plain breaker. This is due to the horizontal moving conductor being remotely situated with respect to the fixed vertical conductors when cross-jet contacts are fitted (Fig. 6). The throw-off forces due to the corner effect which are present with plain breakers are then eliminated, since they cause only internal stresses between the pokers and moving cross-bar. Especially is this the case when the magnetic loop is entirely eliminated as in the designs described.

In reply to Mr. Stedman, the operation of the cross-jet pot has been described by the above authors, but in brief is as follows:—During power arcing it is not possible for any appreciable leakage of oil and gas to occur through the lateral venting jet plates (Fig. 12), since these are blocked by the high back-pressure generated by the arc. In those periods, therefore, a gas cushion under pressure is formed in the metal body surrounding the fixed contact. As the current approaches each zero the arc pressure falls and the expanding gas cushion commences to force a flow of oil and gas through the jets, at the same time holding the arc close to the jet plates. The supply of fluid escapes from the top chamber through the vertical back passage, and to a lesser extent through the smaller contact throat. At the current zero itself these jets commence to cut across the conducting filament of gas through which the small current immediately prior to the zero has been flowing, inserting non-conducting layers of gas and oil between the contacts. It has been determined from oscillograms that the gas-cushion pressure does not have time to become fully relieved in the zero periods and, consequently, becomes higher at each subsequent zero, until, when a sufficient pressure and number of uncovered jets are obtained, interruption occurs.

The short arcing times quoted by Mr. Clothier for his 66-kV single-break design are not strictly comparable with those for the contact of Fig. 12, since with a maximum test current of only 6 000 instead of 30 000 amperes a considerable reduction in throat area would be permissible, with a consequent improvement in performance.

Messrs. Clothier and Farrer have referred to variations occurring in the opening speed during make-break tests. The original single-phase breaker had a no-load speed of 12 ft. per sec., while the 3-phase unit tested on plants "C" and "D" had a speed of 16 ft. per sec. The remainder of the variation at similar currents is accounted for by pre-tripping on certain of the M–B duties, prior to contact making, with the object of parting the contacts on the maximum total current. Under these conditions the breaker may reverse before fully closing, and the throw-off springs do not then give their full accelerating force. In service, the relay cannot be excited before the short-circuit is applied by the breaker, which, therefore, has time to close fully. These variations are obviously no part of the designer's intentions, but are inevitable when tests are made under both pre-tripping and delayed-trip conditions.

In reply to Mr. Blandford, it is true that about 20 per cent increase in opening speed is necessary as compared with the double-break designs, but 100 per cent increase can be obtained with similar mechanisms.

We cannot agree with the argument put forward by Mr. Gregory, that because it appears to be easier to break a high current than a low, a high-kVA breaker need not be any different from one of low kVA at the same voltage. The difficulty of interrupting low currents increases as the maximum current is raised, owing to a necessary increase in venting, while the mechanical troubles are aggravated by increased pot size to contain the greater oil volume found essential with heavy currents. In addition, the stresses throughout the structure rise as the square of the rating. Under the proposed I.E.C. Specification, a testing range of 10 per cent to 100 per cent is called for, and it is found that a lighter and smaller breaker can be designed to interrupt, say, 100 to 1 000 amperes, than 500 to 5 000. Replying to Dr. Garrard and Mr. Dean, in theory it may be desirable for a breaker to be able to interrupt one half per cent of its rated current at a low lagging power factor within its pot, but in practice we do not see how such a range of inductive short-circuit power can occur in one position on a system. Nor have we seen tests published elsewhere made under such conditions, and this value is one-twentieth of the smallest proposed by the I.E.C. Specification referred to above. We therefore consider the fact that such a current associated with phase-to-phase rated voltage was actually interrupted by one phase without damage, to be adequate proof of the ability of design to deal with any service condition.

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* *Journal I.E.E.*, 1932, vol. 71, p. 703.

It was, perhaps, misleading in Table 4 to average the values of two series of tests which were not made at exactly similar voltages and currents. If only those tests which are comparable are considered, i.e. eliminating the first three single-break tests which were made at reduced voltage, it will be found that at the same average currents, voltages, and volt-amperes, the average arc durations and lengths are longer for the single break by 10 per cent. The fact that the first tests were made at a reduced voltage, thus lowering the average volt-amperes as indicated by Dr. Garrard, is purely a testing condition and cannot be held against the single-contact breaker. That this is no isolated performance is emphasized by Mr. Coates's analysis, in which a single-break 66-kV breaker gave a performance superior to that of the analogous double-break type.

The test voltages in Figs. 16 and 17 have not been corrected for power factor and asymmetry, although the analysis in Table 9 in the Appendix has had this combined correction applied.

It may be that at some future date, when a more detailed knowledge of the subject is available, it will be possible to compare tests on different plants by applying a correction factor for the natural oscillating circuit frequencies and damping factors. With present data such a scheme would be premature, as neither service conditions nor the effect of variation in frequencies on different types of modern breaker, nor even the different effects of single-and multi-frequency waveforms, have been fully analysed.

In reply to Mr. Stratton, the plain breaker which arced for 15·7 half-cycles continued arcing when in the fully-open position. In all tests the power factor was 0·1 or less.

The air-blast breaker oscillogram shown by Mr. Wood indicates a remarkably short arc duration, but the term "high-speed breaker" implies a short overall interrupting time from receipt of trip impulse to arc extinction, and, since the trip current is not on the film, this time cannot be determined. It is, however, known that a number of cycles must be added to the time shown for the building-up of the trip-coil current and initiation of the movement of the large main air valves, which are controlled by a servo action.

Design

Mr. Ratcliff has pointed out that one of the features that has made possible the single-break design has been the development of a satisfactory sliding contact. That this contact neither affects unfavourably the interrupting process nor is itself affected by short-circuits, as is suggested by Mr. Blandford, has, we submit, been adequately proved as described in the paper. It has never been necessary to replace any of the sliding contacting parts, and the seizing trouble experienced by Mr. Mellonie does not occur where suitable materials are chosen.

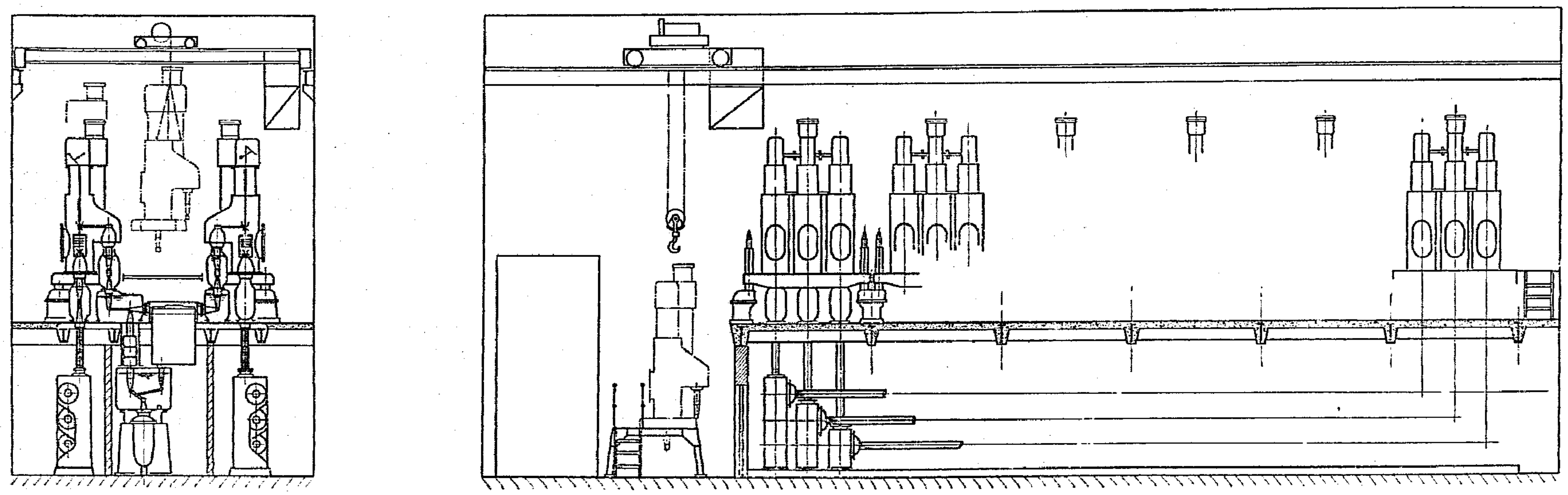
When high-speed operation is required, and especially when this speed must apply to a wide range of short-circuit current, we agree with Mr. Gregory that the impulse type of breaker in which oil is propelled across the arc by mechanical means, has advantages over the more normal designs. The mere pushing of oil into the arc, however, will not necessarily afford the high efficiency associated with certain of these designs, and adequate short-circuit testing is as essential as with other types of breaker.

Considerably divergent opinions have been expressed about the layout of the single-break circuit breaker, and several speakers who grant our theoretical case for this class of gear as proven have put forward their own alternative designs.

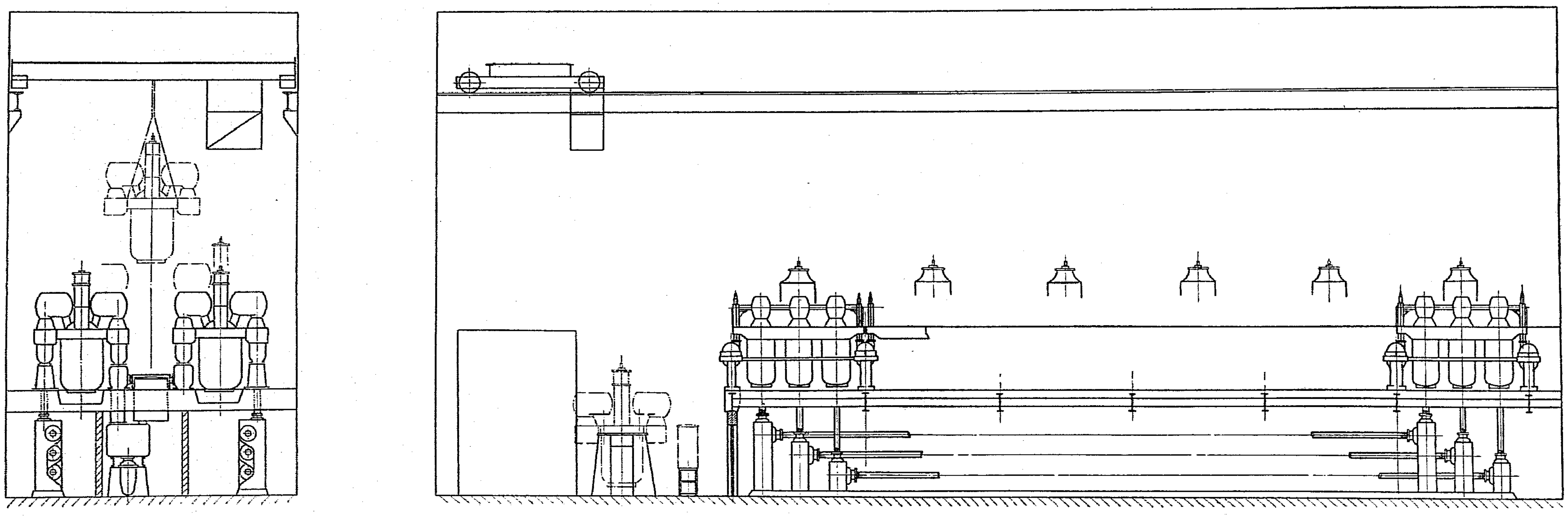
Messrs. Clothier and Allan have constructed a vertical arrangement having a U-shaped moving contact, but requiring concentric type breaker and spout bushings, while Messrs. Trencham and Ferguson advocate different horizontal forms. We ourselves considered a variety of vertical and horizontal arrangements during the development period, and since all have their peculiar advantages we did not expect general agreement on any choice we might have made. Mr. Clothier's criticism that particles of carbon may settle in the pot and cause dielectric breakdown in our arrangement was, however, disproved by a series of 19 short-circuit tests. These were made at both high and low power without change of oil, and the last was followed immediately by a successful sustained over-voltage pressure test supplied from the short-circuit generator and transformer, without removal of voltage from the breaker. We think that Mr. Clothier's Fig. A should be considered together with Fig. 18 of the paper, since it is in plan that the single vertical-break design gains most as compared with double break, while the relative merits of (*a*) or (*c*) can be judged only from complete unit drawings for similar applications.

We are surprised that Mr. Trencham should criticize the lift-up insulating rod, since he has himself been associated with perhaps the only design which has survived successfully without appreciable change the test of 30 years' service, and which still uses such a rod. This satisfactory record seems also the answer to Mr. Blandford in making a similar comment.

Another criticism made of the vertical design is the necessity for an oil-tight door, but in an equipment already requiring a considerable number of such joints



Single-break equipment.



Double-break equipment.

Fig. P

the addition of one more does not seem of great importance. The impulse pressures this door must withstand are offset by the great rigidity of the flanges as compared with normal transformer or switchgear practice.

As regards the application of single-break designs, there is again a similar variation in opinion. Mr. Blandford sees no good in it at all. Mr. Clothier seems to doubt if much advantage can be obtained, but puts forward 66-kV test data and a proposed arrangement. Mr. Ferguson considers our suggested minimum voltage of 22 kV perhaps too low, unless phase separation is necessary. Mr. Trencham believes it may be too high, while Mr. Allan shows a design which has been constructed for 11-kV service. While we do not think that a reduction in material or oil volume can be made at such a low voltage, the possible improvements in performance and reduction in deterioration may make such development worth while.

Both Messrs. Clothier and Allan compare the design of Fig. 19 with their double-break equipments in Figs. B, K, and L. We agree that on duplicate busbar installations, provided no attempt is made to separate the busbars either from each other or from the outgoing circuit, and by the use of their ingenious but complicated sliding bushing isolators, similar overall dimensions may be obtained, but we do not think this will also hold for single busbar equipments. The difficulties associated with the necessary high-voltage spout type bushings are, however, considerable, while on important installations we consider busbar separation to be essential, which accounts for the spacing of the breakers in Fig. 19. This wide spacing does not appear to us to be inconsistent—as suggested by Dr. Garrard—with building the individual breakers to the smallest dimensions for given dielectric clearances, thereby increasing the mechanical factors of safety of the structure. It should also be possible to meet Mr. Kidd's criticism of Fig. 20 by inserting a concrete partition between the busbars. That a 50 per cent building saving is obtained with 66-kV single-break gear as compared with a double-break oval tank arrangement affording equal safety is shown in Fig. P.

If, however, Mr. Clothier's design having busbars arranged in close proximity is acceptable, then a considerably more compact design of single-break structure becomes possible, as shown in the 132-kV comparison in Fig. Q, which is still at least as accessible as the sliding bushing alternative, while the ground area is some 16 per cent less.

Mr. Allan criticizes our fixed designs on the score that maintenance work must be carried out in close proximity to live conductors, but a metal barrier and positive visible earthing have in the past been considered as safe. Also his own design suffers from this same defect, if defect it be. Contact inspection and similar work requires the removal of the breakers, but this must be done by men separated from the busbars by a metal barrier only, while the removal and replacement of these breakers will possibly take more time than does the complete overhaul for single-break gear. Moreover, it does not seem practicable to operate the three phases of the breaker when removed by means of their own mechanism for contact checking purposes—a disadvantage in maintenance work.

Messrs. Allan and Kingsbury both imply that we have sacrificed accessibility, but we think the maintenance times given by Mr. Main justify our claim to improved facilities in this respect. This will be all the more marked in comparison with any e.h.t. floor-mounted breaker the maintenance of which type is referred to by Mr. Davidson. Single-break installations now under construction are also being supplied with tanks for clean and dirty oil as he suggests.

The insulated design of cross-jet pot shown in Fig. 12, which, as Mr. Coates points out, has made practicable high-voltage designs, has also been mounted in some equipments with breech-block fastenings, which would reduce still further the times shown by Mr. Main.

Messrs. Ferguson and Trencham criticize the fixed-breaker design of Fig. 11, which has been in actual service in several installations for two years, on the score that if structural distortion occurs due to failure, repair is more difficult. The withdrawable breaker, however, in this unlikely event may easily become totally immovable, while for outdoor use the fixed design appears to us almost essential to a sound design.

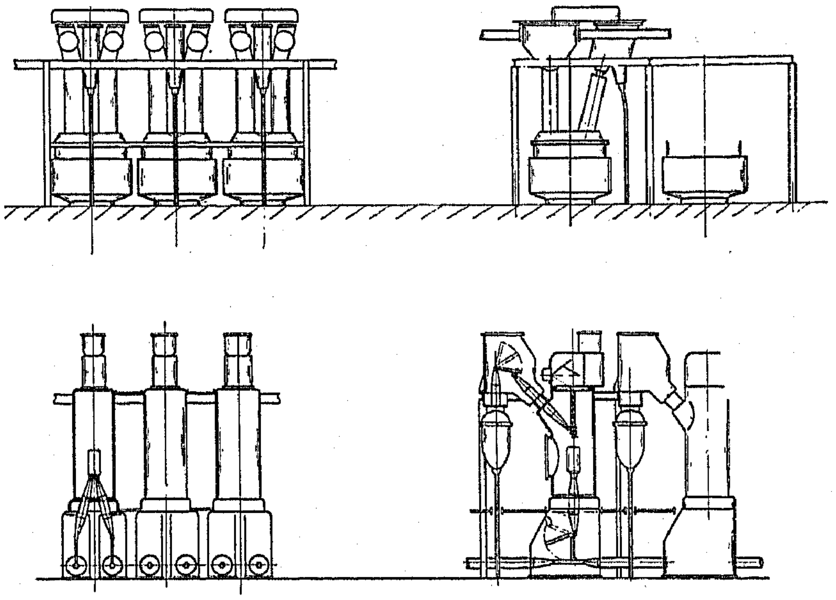


Fig. Q.—Comparison between 132-kV single- and double-break designs.

In reply to Messrs. Main and Davidson, designs up to 132 kV as mentioned in the paper are quite practicable for either indoor or outdoor single-break equipments, and their more complete development awaits only a demand from the industry.

Messrs. Garrard and Harris criticize oil-filled metalclad gear on account of the number of chambers, but we think it is generally accepted that a design having many small subdivided oil chambers requiring little if any maintenance is preferable to the alternative having a number of large cubicles necessitating elaborate interlocking and cleaning, and even then not affording the same safety to operators. The current-transformer chamber of Fig. 21 is air-filled, the oil-level line in the isolating chamber "D" having been inadvertently omitted.

Mr. Blandford finds a further failing in the single-break design, in that it has no magnetic loop to aid in accelerating the contacts. Since, as shown by test, the breaker does not require any such additional acceleration, this is of no consequence, and at 22 or 33 kV is in fact an advantage in reducing the " making " throw-off force to be dealt with by the mechanism of breakers of high rated capacity.

We agree with Mr. Kidd that exactly simultaneous making of a 3-phase circuit is not essential—although these designs do not differ from the normal in this respect—while simultaneous breaking is in any case impossible, the last two phases always requiring an additional period of about ¼ cycle. The contacting faces of the contacts are of line type.

Figs. 20 and 21 are perhaps not very clear, since the fixed contacts are not carried in cantilever as interpreted by Mr. Dean, but by two bracing bars which are discernible in section on either side. In reply to Mr. Burgess, magnetic latches consisting of a magnet and armature can be employed to replace mechanical latches. An armature holds in the mechanism through the usual system of toggles, and it is tripped by diverting the flux through a leakage path, affording a fast release equivalent to that obtained on d.c. high-speed breakers for traction service.

The busbars at the bottom of Fig. 20 criticized by Dr. Garrard have been in reliable service for many years and are in fact rounded at their edges; the design shown, using compound filling, is intended for indoor use, as oil should of course be employed out of doors.

In reply to Messrs. Mellonie and Stratton, the feeder cable can be earthed through the breaker of Fig. 11 by closing the earthing switch (D).

The ratio of oil volumes requested by Mr. Solomon for single- to double-break breakers of 33 kV, 1 500 MVA, with phase separation, would be about 3 to 5. At the suggestion of Mr. Dean we have added scales on representative layouts at 33 and 66 kV.

Costs

A number of speakers have referred to costs, indicating that the single-break unit should be either cheaper or more expensive than the normal. The continued development in the interests of higher speed and greater reliability has prevented any stabilization of design, and until this is brought about economies are likely to remain indirect—as building and maintenance reductions and in the form of insurance, inasmuch as better protection is available. We do not, however, consider the comparison of cost per kVA given by Mr. Dean to be a correct presentation of the case. The duty of a circuit breaker is more analogous to that of a gun than to that of a cable, and we believe that in all probability the cost of the former rises more rapidly than their calibre or weights. The single-break design seems to us, however, to be justified on purely technical grounds whether the cost be less than, the same as, or greater than, for a normal breaker.

In conclusion we should like to express our appreciation of the interesting and controversial discussions which have taken place. Our object in presenting this paper was partly to give a theory and its proof in justification of single-break design, and to dispel the old idea that multi-break designs must inherently be better, regardless of their type. Our theory we believe to have been generally accepted, and the number of alternative single-break designs now put forward bears out this conclusion. It was also to describe our actual tested designs, some of which have been constructed and are in service. These have met with a more varied reception, but we believe the final criterion to be their actual and satisfactory operation under service conditions.

THE THEORY AND DESIGN OF HOT-WIRE AMMETERS FOR FREQUENCIES OF 25 TO 100 MEGACYCLES

By Professor C. L. FORTESCUE, O.B.E., M.A., Member.

(*Paper first received* 3*rd December*, 1935, *and in final form* 18*th January*, 1936; *read before the* Wireless Section 1*st April*, 1936.)

SUMMARY

This paper contains an account of the advances in design and theory of the screened hot-wire ammeters described in 1930. The design has been improved both mechanically and electrically, leading to more compact instruments of lower impedance. These improvements have arisen from a more careful consideration of the temperature distribution in the hot wire, the behaviour of the magnifying system, and the corrections necessary at high frequencies. The results of experience with a number of experimental instruments are given and constitute a basis for any further designs that may be required.

LIST OF SYMBOLS

A = area of cross-section, in cm^2.

E = Young's modulus, in dynes per cm^2.

f = frequency, in megacycles per sec.

h = rate of dissipation of energy from surface of hot wire, in watts per cm^2 per deg. C. temperature-rise.

I_0 = amperes (d.c.) carried by hot wire.

l = length, in cm.

P_0 = watts expended in hot wire at air temperature when current in it is I_0.

p_1 = pull at mid-point of sagging wire, with pointer in zero position.

p_2 = pull at mid-point of sagging wire, with pointer in load position.

$R_{a.c.}$ = a.c. resistance per cm length of hot wire.

$R_{d.c.}$ = d.c. resistance per cm length of hot wire.

R_m = measured resistance of sample of wire of length l_m and diameter d.

S = area of surface of hot wire, in cm^2 per cm length.

s = sag of hot wire in zero position of pointer, in cm.

T_1 = tension in sagging wire, with pointer in zero position.

T_2 = tension in sagging wire, with pointer in load position.

x = distance, in cm.

α = coefficient of increase of resistance per deg. C.

β = coefficient of increase of rate of cooling per deg. C.

θ = temperature-rise of hot wire above surrounding atmosphere, in deg. C.

κ = thermal conductivity of material of hot wire, in watts per cm^2 per deg. C. per cm length.

LIST OF SYMBOLS—*continued.*

ρ = specific resistance of material of hot wire at atmospheric temperature, in ohms per cm per cm^2.

K_1 and K_2 = constants relating to temperature distribution in hot wire.

INTRODUCTION

A form of screened hot-wire ammeter suitable for use over the range of frequency 25–100 megacycles was described by the present author in 1930.* Experience of the use of these instruments and of the design and construction of improved forms which has been gained since that date is embodied in this paper.

The subject matter naturally divides itself into the following sections: (1) The thermal conditions prevailing in the hot wire; involving a knowledge of the various physical constants of the materials of the wire. (2) The mechanical magnifying system. (3) The electrical correction due to change of effective resistance with frequency. (4) The calculation of the correction factors; including the corrections for the change of resistance, for the distributed inductance and capacitance of the wire, and for the terminal capacitance. (5) Mechanical details of construction. Some parts of this schedule, particularly Sections (3) and (4), were dealt with in the earlier paper, and only small extensions are included here.

As was pointed out in the earlier paper, one disadvantage of these instruments is that the length of hot wire which is convenient from the thermal and mechanical points of view, leads to the electrical impedance becoming inconveniently high. Attempts have been made to reduce the impedance without introducing other difficulties, and some parts of this paper relate rather particularly to the problems encountered in this new design.

The only material that has been used for the hot wires is a platinum-silver alloy similar to, if not identical with, that used in the original Hartmann–Braun design of some 40 years ago. This alloy consists of approximately 33 per cent platinum and 67 per cent silver. It has the advantage that both the specific resistance and the coefficient of linear expansion are fairly high; that it can be worked for long periods in ordinary atmosphere at temperatures of from 200° C. to 300° C. without appreciable oxidization of the surface; that it is non-magnetic; and that the mechanical properties are good, the material being similar in this respect to phosphor bronze.

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* *Journal I.E.E.*, 1930, vol. 68, p. 556.

The general tendency of the mechanical design has been in the direction of rendering the instruments more compact and less liable to injury arising from projecting terminals coming into contact with external obstacles.

(1) THE THERMAL CONDITIONS PREVAILING IN THE HOT WIRE

(a) Boundary Conditions and Approximations

The following assumptions are necessary to enable the temperature distribution to be calculated:—

(i) Owing to the relatively large mass of metal to which the wire is attached at each end and the large cooling area which this presents, it is assumed that the temperature at each end of the wire is that of the surrounding air, i.e. at both $x = 0$ and $x = l$, $\theta = 0$.

(ii) It is assumed that the thermal conductivity of the material of the hot wire is independent of the temperature. This assumption is convenient from the point of view of the simplification of the mathematics and is justifiable on the grounds that the variation of the thermal conductivity with temperature seems never to have been ascertained, and that in most practical cases the maximum temperature of the wire is only slightly dependent on the thermal conductivity of the material.

(iii) As is pointed out in the next paragraph, a somewhat similar approximation has to be made with respect to the coefficient (h) which gives the rate of dissipation of energy from the surface of the wire.

(b) Calculation of Temperature Distribution

Considering a length δx of the hot wire at distance x from the left-hand end (see Fig. 1), the temperature-rise above the surroundings being θ; the rate of generation of heat in the element will be

$$I_0^2\rho(1 + \alpha\theta)\frac{\delta x}{A}$$

The rate of dissipation from the surface will be

$$h(1 + \beta\theta)s \,.\, \delta x \,.\, \theta$$

The rate of conduction of heat away from the element is

$$-\,\kappa A\frac{d^2\theta}{dx^2}\delta x$$

For steady conditions, therefore,

$$\frac{d^2\theta}{dx^2} = \frac{h\beta S}{\kappa A}\theta^2 + \frac{AhS - I_0^2\rho\alpha}{\kappa A^2}\theta - \frac{I_0^2\rho}{\kappa A^2} \quad . \quad . \quad (1)$$

This equation is not easily integrated unless the term in θ^2 can be rendered negligible by taking a mean value of h, so assuming β to be zero. In that case the equation becomes

$$\left.\begin{aligned} &\frac{d^2\theta}{dx^2} = K_1^2\theta - K_2^2 \\ \text{where}\quad &K_1^2 = \frac{AhS - I_0^2\rho\alpha}{\kappa A^2} \\ \text{and}\quad &K_2^2 = \frac{I_0^2\rho}{\kappa A^2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The solution of (2) when K_1^2 is positive (as is always the case), and with the limits $\theta = 0$ both when $x = 0$ and when $x = l$, is

$$\theta = \frac{K_2^2}{K_1^2}\left[1 - (\cosh K_1x - \tanh\frac{K_1l}{2}\sinh K_1\alpha\right] \quad . \quad (3)$$

The maximum value of θ occurs when $x = l/2$, and is given by

$$\theta_{max} = \frac{K_2^2}{K_1^2}\left(1 - \operatorname{sech}\frac{K_1l}{2}\right) \quad . \quad . \quad . \quad (4)$$

The mean value of θ is given by

$$\bar{\theta} = \frac{2}{l}\int_0^{\frac{l}{2}}\theta dx = \frac{K_2^2}{K_1^2}\left(1 - \frac{2}{K_1l}\tanh\frac{K_1l}{2}\right) \quad . \quad . \quad (5)$$

and the ratio $\theta_{max}/\bar{\theta}$ is given by

$$\frac{\theta_{max}}{\bar{\theta}} = \frac{1 - \operatorname{sech}\dfrac{K_1l}{2}}{1 - \dfrac{2}{K_1l}\tanh\dfrac{K_1l}{2}} \quad . \quad . \quad . \quad (6)$$

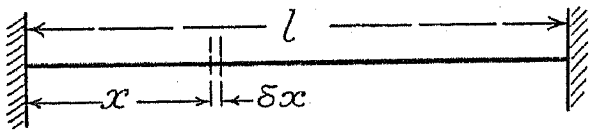


Fig. 1

When $\epsilon^{K_1l/2}$ is much larger than unity, equation (6) becomes

$$\frac{\theta_{max}}{\bar{\theta}} = \frac{1}{1 - \dfrac{2}{K_1l}} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

It is interesting to note that if $P_0 = I_0{}^2R$, i.e. P_0 = watts expended in wire at air temperature when current in it is I_0, then

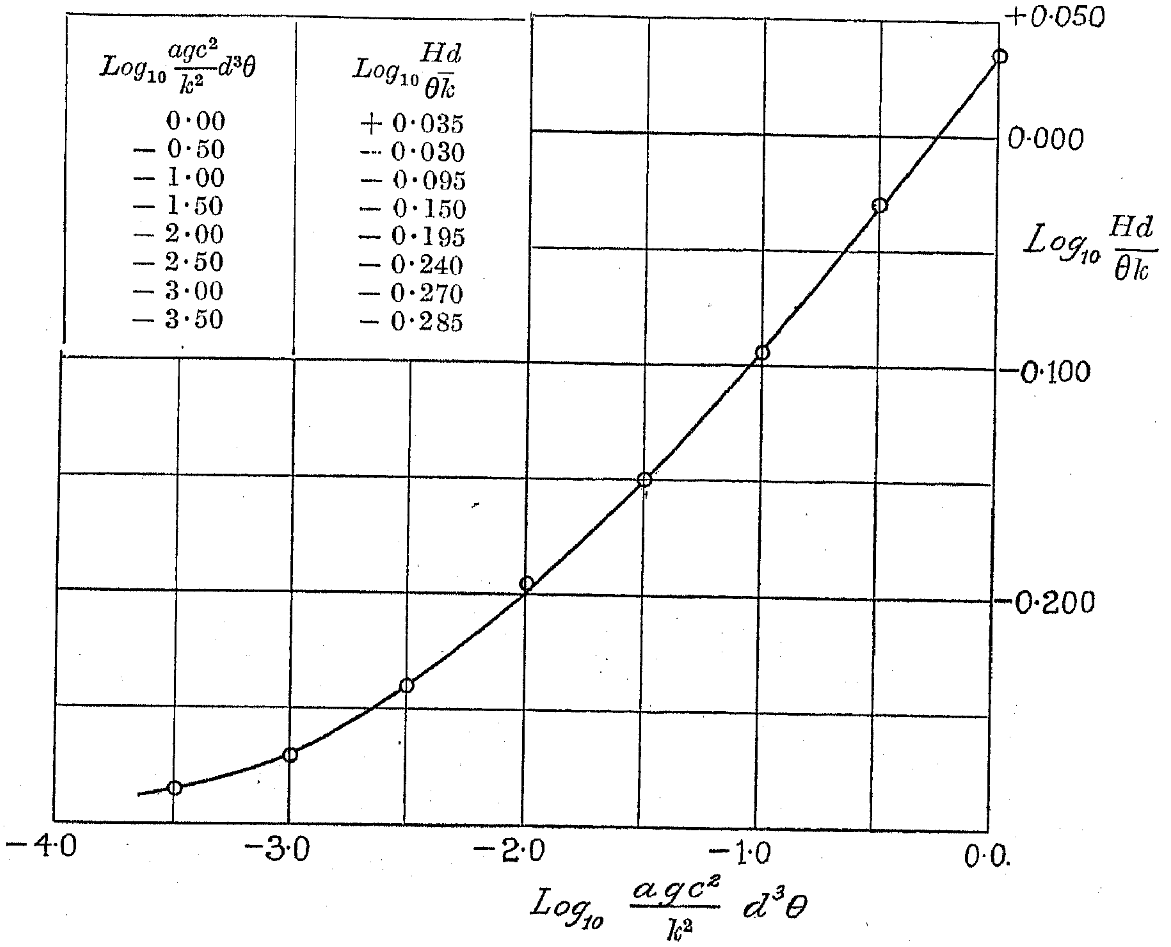
$$\left.\begin{aligned} K_1^2 &= \frac{hlS - \alpha P_0}{\kappa Al} \\ K_2^2 &= \frac{P_0}{\kappa Al} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (8)$$

and

$$\frac{K_2^2}{K_1^2} = \frac{P_0}{hlS - \alpha P_0} \quad . \quad . \quad . \quad . \quad (9)$$

(c) The Constants ρ and α

The values of the constants ρ and α of equations (3) to (7) are easily determinable for any given sample of wire. With the platinum-silver alloy used in these ammeters, the value of ρ varies considerably from sample to sample and careful resistance measurements are necessary in all cases. The value of α has only been found accurately for one sample of wire. For this sample the value of ρ at 20° C. was $32{\cdot}0 \times 10^{-6}$ ohm per cm per cm^2, and the value of α for the range 20° C. to 160° C. was $2{\cdot}53 \times 10^{-4}$ per degree C. Wire from



$Log_{10}\frac{agc^2}{k^2}d^3\theta$	$Log_{10}\frac{Hd}{\theta k}$
0·00	+ 0·035
– 0·50	– 0·030
– 1·00	– 0·095
– 1·50	– 0·150
– 2·00	– 0·195
– 2·50	– 0·240
– 3·00	– 0·270
– 3·50	– 0·285

Fig. 2

this reel has been used in several ammeters in which the current per wire is 1 ampere.

(d) The Constant *h*

The constant *h* presents difficulties, and certainly varies considerably with the wire diameter. Fishenden and Saunders* have collected together most of the available information with respect to the cooling of wires in any atmosphere and under conditions of natural convection. They have plotted a curve (Fig. 17, page 97 of their book) giving the logarithm of a quantity $(agc^2/k^2)d^3\theta$ in terms of the logarithm of $Hd/(\theta k)$, where a denotes the coefficient of expansion of the gas, g denotes the acceleration due to gravity, c denotes the specific heat at constant pressure of the gas, k denotes the thermal conductivity of the gas, d denotes the diameter of the wire, θ denotes the temperature-difference between the surface of the wire and the surrounding gas, and H denotes the total heat-transfer per unit area of the wire, per unit time.

The relevant part of this curve is reproduced in Fig. 2 of this paper.† The physical constants vary with temperature, and in this curve they are given the values corresponding to temperatures midway between those of the wire and of the surrounding air; the latter being taken as 65° F. (18° C.). Values of k and of agc^2/k^2 are also given in the book (page 256). The values of k (in watts per cm² for a temperature gradient of 1 deg. C. per cm length) and of log (agc^2/k^2) (in similar units) are given in Fig. 3. In these curves the corrections arising from the fact that the constants must have values corresponding to the mean of the air and wire temperatures have been made, and both curves are plotted in terms of the actual temperature of the wire; the surrounding air being assumed to be at a temperature of 18° C.

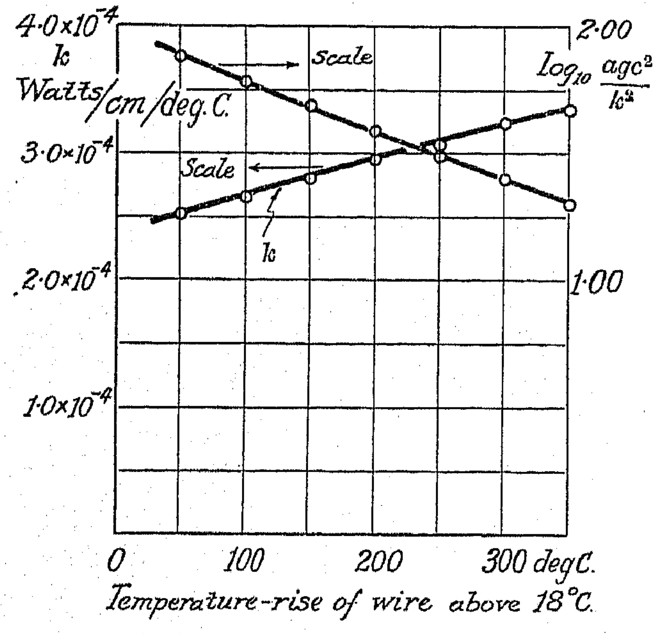


Fig. 3

Thus for any rise of temperature θ deg. C. above the surrounding air, the value of $\log_{10}(agc^2/k^2)$ is found from Fig. 3, and $\log_{10}\left(\frac{agc^2}{k^2}d^3\theta\right)$ then follows for any given size of wire and for any given temperature-rise. Fig. 2 gives the corresponding value of $\log_{10}(Hd/k\theta)$; Fig. 3 gives the value of k, and so H/θ is obtained. The value of h, in watts per cm^2 per deg. C. temperature-rise, can then be calculated.

---

* "The Calculation of Heat Transmission" (H.M. Stationery Office, 1932).

† By permission of the Controller, H.M. Stationery Office.

Detailed calculations for the case of $d = 0{\cdot}01588$ are given in Table 1.

Table 1

θ	$\log_{10}\left(\frac{a\rho c^2}{k^2}d^3\theta\right)$	$\log_{10}\left(\frac{Hd}{k\theta}\right)$	$\frac{Hd}{k\theta}$	$\frac{k}{d}$	h
deg. C.					
50	− 1·82	− 0·179	0·66	0·0156	0·0104
100	− 1·62	− 0·160	0·69	0·0165	0·0114
150	− 1·54	− 0·153	0·70	0·0176	0·0124
200	− 1·52	− 0·151	0·71	0·0185	0·0131
250	− 1·51	− 0·150	0·71	0·0194	0·0137
300	− 1·52	− 0·151	0·71	0·0203	0·0143
350	− 1·56	− 0·155	0·70	0·0209	0·0146

Plotting h in terms of θ enables an estimate to be formed of the approximate mean value which may be assumed for purposes of calculation. For a maximum temperature-rise in the neighbourhood of 250° C. an approximate value for this size of wire would appear to be $h = 1{\cdot}2 \times 10^{-2}$. The curves of h in terms of θ for five sizes of wire are shown in Fig. 4. From these the mean values given in Table 2 are estimated on the assumption that the maximum temperature is in the neighbourhood of 250° C.

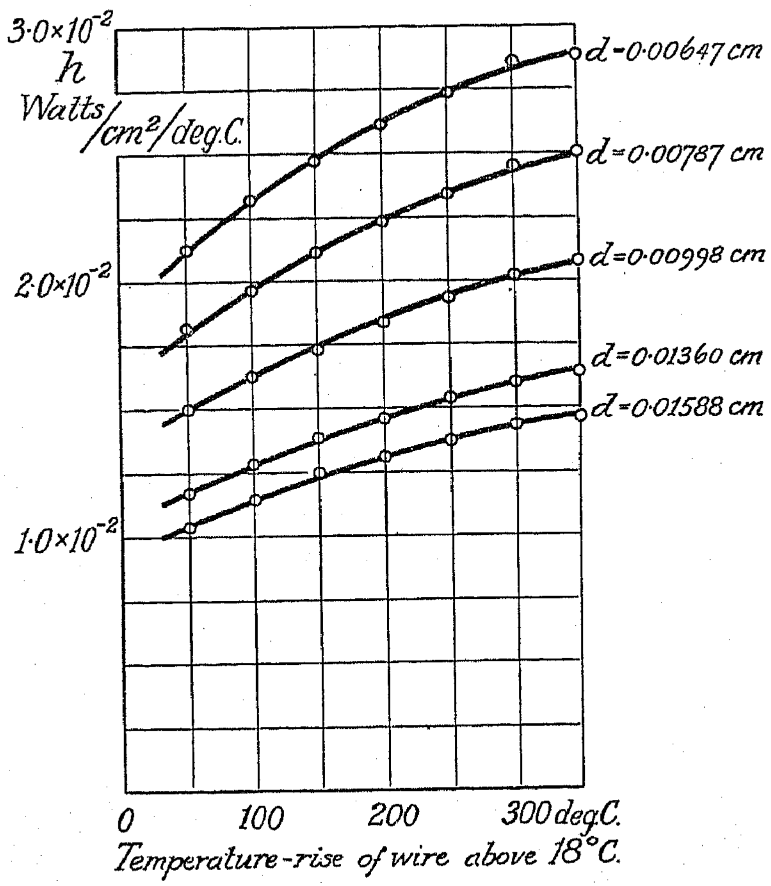


Fig. 4

Table 2

Diameter of wire	h
cm	watts/cm^2.deg. C.
0·01588	$1{\cdot}2 \times 10^{-2}$
0·01360	$1{\cdot}3 \times 10^{-2}$
0·00998	$1{\cdot}6 \times 10^{-2}$
0·00787	$2{\cdot}0 \times 10^{-2}$
0·00647	$2{\cdot}4 \times 10^{-2}$

It is convenient to plot these values of h in terms of d, as in Fig. 5, since wires of intermediate sizes are used in some cases.

(e) The Constant κ

The International Critical Tables give $\kappa = 0{\cdot}30$ watt per cm per deg. C. for a platinum-silver alloy containing 33 per cent platinum. Considerations of Lorenz's law that the product of the electrical resistivity and the thermal conductivity is constant, suggest that κ increases with the temperature.

For platinum, $\kappa = 0{\cdot}695\,(1 + 0{\cdot}0005\theta)$ and $\rho = 11{\cdot}4 \times 10^{-6}\,(1 + 0{\cdot}0038\theta)$. For 33 per cent Pt-Ag alloy, $\rho = 31{\cdot}6 \times 10^{-6}\,(1 + 0{\cdot}00025\theta)$. Thus, assuming Lorenz's law to be applicable, it would appear that, for a 33 per cent Pt-Ag alloy,

$$\kappa = \frac{0{\cdot}695 \times 11{\cdot}4}{31{\cdot}6}\left[\frac{(1 + 0{\cdot}0005\theta)\ \ (1 + 0{\cdot}0038\theta)}{1 + 0{\cdot}00025\theta}\right]$$
$$= 0{\cdot}25\,(1 + 0{\cdot}004\theta)$$

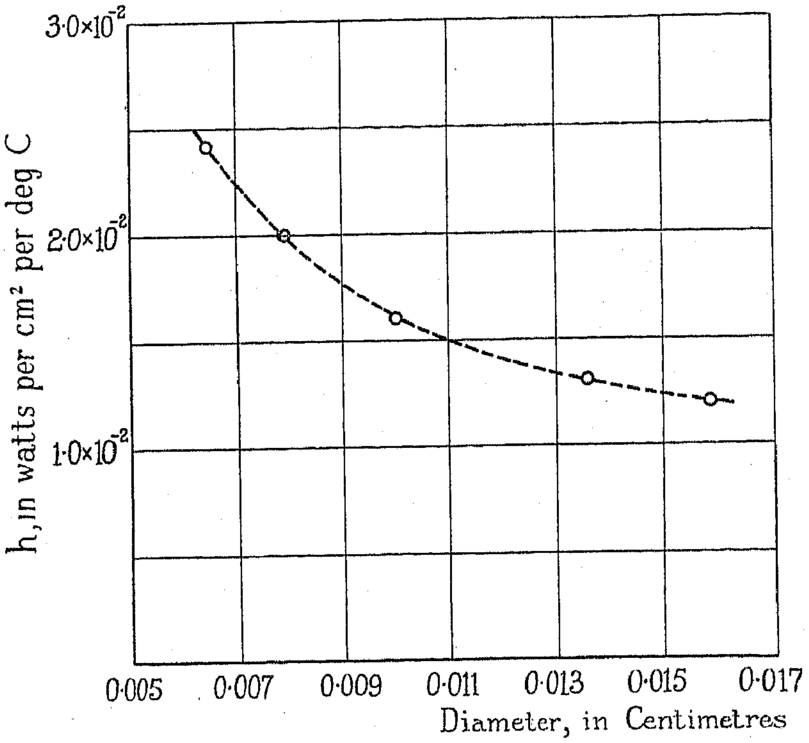


Fig. 5

For a value of θ of about 250 deg. C., the mean value of κ would appear to be 0·375. A similar calculation based on the known values of κ and ρ for silver gives, for a Pt-Ag alloy having 33 per cent Pt, the value

$$\kappa = 0{\cdot}216\,(1 + 0{\cdot}004\theta)$$

and if $\theta = 250$ deg. C. the appropriate mean value of κ is 0·32. A reasonable mean value to be ascribed to κ would thus appear to be 0·35.

(f) Comparison of Calculated and Observed Temperatures

In view of the uncertainty with regard to the specific constants of the material of the wires and to doubts in some cases with regard to the true diameters, it is no

Table 3

Serial No. of instrument	6	10	11	12	14
Number of hot wires	1	4	4	1	4
Length of wires (cm)	10·2	8·1	7·64	10·2	2·52
Diameter of wires (cm)	0·0061*	0·00787†	0·0145‡	0·0102*	0·01588‡
Specific resistance (ohm/cm/cm^2)	$32\cdot6 \times 10^{-6}$	$35\cdot5 \times 10^{-6}$	$26\cdot1 \times 10^{-6}$	$30\cdot4 \times 10^{-6}$	$32\cdot4 \times 10^{-6}$
Full-load current (amps.)	0·25	2·00	4·00	0·50	4·00
Calculated mean temperature-rise (deg. C.)	146	380	274	200	190
Observed mean temperature-rise (deg. C.), assuming $\alpha = 2\cdot53 \times 10^{-4}$	153	348	250	189	207

* Reputed. † Probable. ‡ Measured.

to be expected that a very exact agreement between calculated and measured temperatures will be found.

The only actual measurement of temperature that can be conveniently made is that based on the increase of resistance, and this involves a knowledge of the temperature coefficient of the particular wire on which the observations are made. The wires actually used have come from various sources, and the value of the temperature coefficient may vary appreciably. The value given in Section (1) (*c*), namely $2\cdot53 \times 10^{-4}$, is rather less than that given in the International Critical Tables, namely $2\cdot6 \times 10^{-4}$, and the mean temperatures determined in this way may possibly be in error to a similar extent. The mean temperature calculated from equation (5) with the values of the constants derived above, and the mean temperature determined by the observed increase of resistance and calculated on the assumption that $\alpha = 2\cdot53 \times 10^{-4}$, are given in Table 3, for five instruments of very different designs.

Table 4

Ammeter Serial No.	6	10	11	12	14
Maximum temperature-rise (deg. C.)	158	368	274	200	280

These results agree on the whole more closely than would have been expected, and certainly justify the use of equation (7) for determining in any particular case the ratio of the maximum temperature to the mean temperature. Assuming the mean temperature derived from the increase of resistance to be substantially correct for the five instruments to which reference is made in Table 3, the corresponding actual maximum temperatures can be found and are given in Table 4.

The high temperature-rise of ammeter No. 10 is remarkable. The instrument has been in use for some years and has recently been submitted to a full-load test of 138 hours' continuous running. A slight change of constitution of the alloy evidently occurred, since the resistance decreased by about 1·4 per cent and the calibration required correction to this extent. In all other respects the instrument was satisfactory.

(g) Conclusions with regard to Temperature of Hot Wires

The most important consideration is obviously that of the maximum temperature. With most of the earlier instruments the ratio of length to diameter of the wire is such that the maximum temperature differs but little from the mean. But in the later designs in which the impedance has been reduced as far as possible, this is by no means the case, and careful calculation and comparison with existing instruments is necessary in order to reach a reliable conclusion as to whether any particular wire can safely carry any particular current. Though the absolute accuracy of the calculated temperature-rise is very doubtful, the relative accuracy is certainly high enough for design purposes. A calculated maximum temperature-rise of about 250 deg. C. appears to be a satisfactory guide and provides for a reasonable overload capacity.

(2) MECHANICAL MAGNIFYING SYSTEM

(a) Coefficient of Linear Expansion of Platinum-Silver Wires

The generally-accepted figure for the coefficient of linear expansion of 33 per cent platinum alloy is 15×10^{-6}. Thus for a length l and a mean temperature-rise θ, the extension of the wire will be given by

$$\delta l = 15 \times 10^{-6} l\theta$$

The calculated and observed extensions for four of the five instruments referred to in Table 3 are thus as shown in Table 5.

The measured extensions are obtained by means of a measuring microscope, but it is difficult to get a high degree of accuracy. The agreement is, however, reasonably good.

Table 5

Ammeter Serial No.	6	10	11	14
Estimated extension (cm)*	0·023	0·042	0·029	0·0078
Measured extension (cm)	0·021	0·05	0·03	0·008 (mean)

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* Based on the mean temperature-rise derived from actual resistance measurement.

(b) Torque on Spindle carrying Pointer

The pointer is operated by a silk fibre passing round a small pulley on a spindle and kept taut by a light spring. The maximum tension in the silk thread thus occurs at the zero reading, and this maximum tension multiplied by the radius of the pulley gives the maximum balanced torque on the moving system. This torque corresponds to the full-scale deflecting and restoring torques in other types of instruments.

Tensions in the silk fibre of from 750 to 4 000 dynes and pulley diameters of from 0·3 to 0·5 cm have been used. The torques on the moving system have therefore varied from about 250 to 2 000 dyne-cm, and are thus of the same order as those found in ordinary commercial pointer instruments.

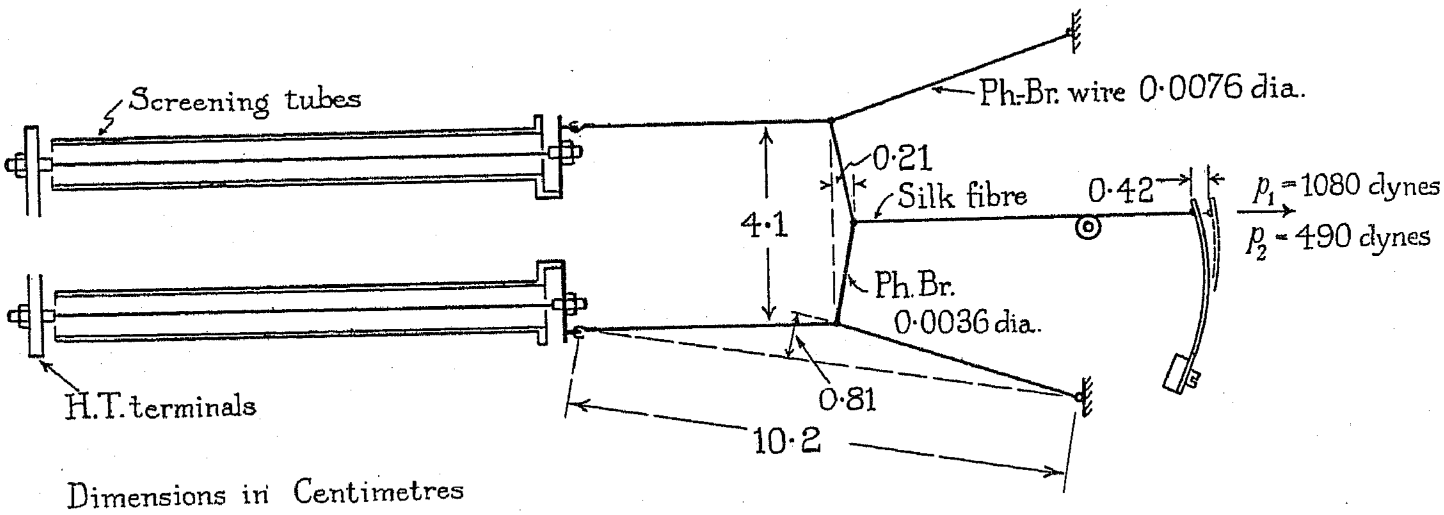

Fig. 6

(c) Actual Displacement of Point of Attachment of Silk Thread

The movement of the silk thread from no load to full load is determined by the angle through which the pointer is to be turned and by the diameter of the pulley on the spindle. With scales of about 15 cm diameter a movement of the pointer through about 90° has generally been provided. Actually 60° would be ample for the degree of accuracy to be expected at a frequency of 50 megacycles. Increase of scale length does not increase the accuracy, and in the later design an angular displacement of 60°—giving a scale length of 7 cm—has been considered adequate.

In instruments in which a displacement of 90° has been provided and in which pulley diameters of 0·5 cm have been used, the actual movement is about 0·4 cm. With a pulley diameter of 0·3 cm the actual movement for an angle of 60° is, however, only 0·16 cm.

The most convenient compromise is determined by the safe working tensions and the space available for the magnifying system. If the tensions in any part of the system are too high, evidences of slow extension show themselves by the fact that, when not in use, the pointer slowly moves from zero over the scale. This extension seems usually to occur in the attachment of the wires and silk fibres rather than in the wires and fibres themselves, though these are fairly heavily stressed. A satisfactory compromise can only be found by a process of trial and observation, in which the quality of the workmanship plays a predominating part. A tension of 2 000 dynes, a pulley diameter of 0·4 cm, and an actual lateral movement of the silk thread of 0·3 cm, are reasonable figures as a preliminary guide to the designing of the magnifying system.

(d) Types of Magnifying Systems

The only magnifying systems used have been developments of the original Hartmann–Braun sagging-wire system, adapted to use the extension of two or four of the hot wires in the multiple-wire instruments.

One system using flexible end-covers to the screening tubes, which were themselves expected to contribute a magnification of about 1·5, is shown in Fig. 6. This makes use of the extension of two of the hot wires and is a symmetrical system. It has been used on several 4-wire ammeters. The wire extension on full load is 0·03 cm, and the movement of the silk thread over the pulley is 0·4 cm, the value of the magnification derived from the extension of two wires being about 13.

The system used in the low-impedance ammeter No. 14 is that shown in Fig. 7. Here the extension of all four wires is used, but the rather doubtful multiplication obtained from the end covers of the screening tubes in the arrangement of Fig. 6 has been abandoned in order to reduce to a minimum the inductance of the circuit between the ends of the wires and the screening tubes. With this system the wire extension on full load is 0·008 cm and the movement of the silk fibre over the pulley about 0·2 cm, giving a magnification of 25 derived from the extension of all four wires.

Fig. 8 shows a compact arrangement for use with an ammeter in which the overall dimensions have been reduced to a minimum.

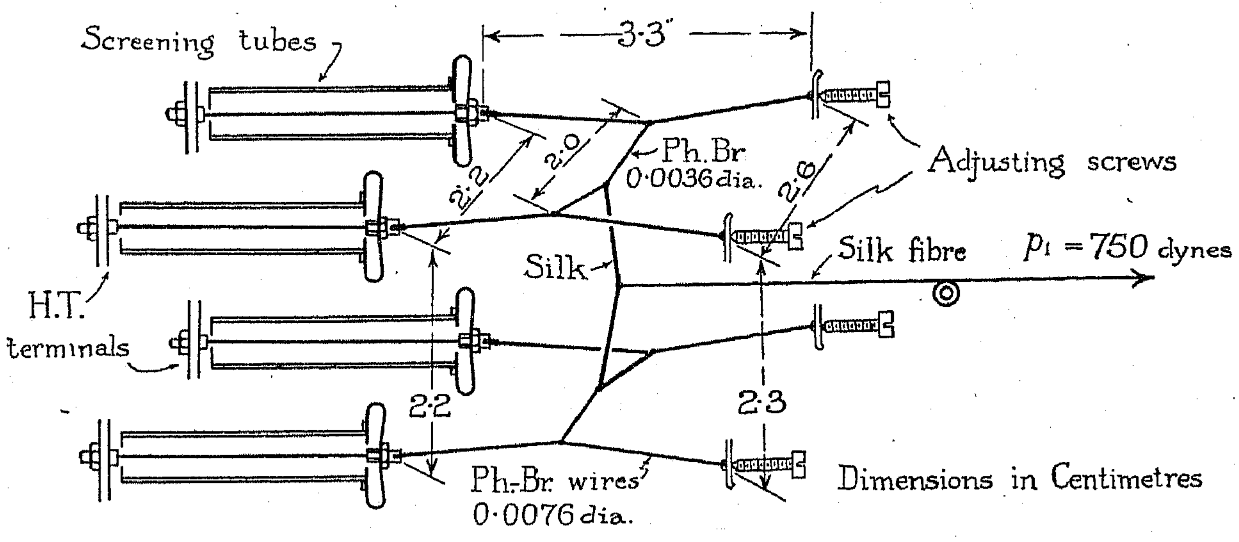

Fig. 7

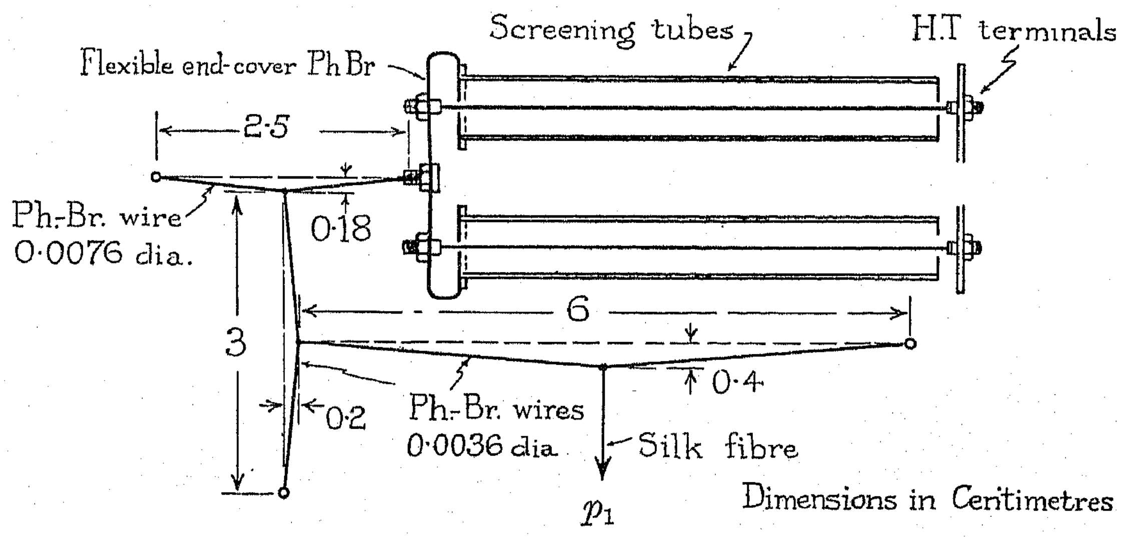

Fig. 8

(e) Calculation of Sag

Consider one of the sagging-wire systems shown in Fig. 9, in which x denotes the initial spacing of the ends of the wire, $\delta x/2$ denotes the inward movement of each end, δs denotes the increase of sag as the pointer moves to the load position, and $\delta_1 l$ and $\delta_2 l$ respectively denote the elastic extensions of the wire in the zero position and the load position of the pointer. The remainder of the symbols employed in the analysis which follows are given in the List of Symbols (see page 179).

For the initial position of the pointer,

$$\left(\frac{x}{2}\right)^2 + s^2 = \left(\frac{l + \delta_1 l}{2}\right)^2 \quad . \quad . \quad . \quad (10)$$

$$2T_1 \frac{s}{\frac{1}{2}(l + \delta_1 l)} = p_1 \quad . \quad . \quad . \quad . \quad (11)$$

$$\delta_1 l = \frac{T_1}{A}\frac{l}{E} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

whence

$$x^2 = 4s^2 \left\{ \frac{1}{\left[\frac{2s}{l} - \frac{1}{2}\frac{p_1/A}{E}\right]^2} - 1 \right\} \quad . \quad . \quad (13)$$

When the pointer is moved to the load position the corresponding equations are

$$\left(\frac{x - \delta x}{2}\right)^2 + (s + \delta s)^2 = \left(\frac{l + \delta_2 l}{2}\right)^2 \quad . \quad (10a)$$

$$2T_2 \frac{s + \delta s}{\frac{1}{2}(l + \delta_2 l)} = p_2 \quad . \quad . \quad . \quad . \quad (11a)$$

$$\delta_2 l = \frac{T_2}{A}\frac{l}{E} \quad . \quad . \quad . \quad . \quad . \quad (12a)$$

whence

$$(x - \delta x)^2 = 4(s + \delta s)^2 \left\{ \frac{1}{\left[\frac{2(s + \delta s)}{l} - \frac{1}{2}\frac{p_2/A}{E}\right]^2} - 1 \right\} \quad (13a)$$

These equations must be applied successively from one end to the other of the system, the change of sag of one system giving the δx of the next one when due allowance is made for whether both ends of the sagging wire move or only one of them.

Full allowance is made for the elastic extension of the sagging wire in equations (13) and (13a), though actually this is often negligibly small. When this is the case these equations become:—

$$x^2 = l^2 - 4s^2 \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$(x - \delta x)^2 = l^2 - 4(s + \delta s)^2 \quad . \quad . \quad . \quad (14a)$$

For those cases in which both $4s^2/l^2$ and $4(s + \delta s)^2/l^2$ are small compared with unity, equations (14) and (14*a*) give

$$\delta x = \frac{2\delta s}{x}(2s + \delta s) \quad . \quad . \quad . \quad . \quad (15)$$

and if, further, δs is much smaller than s,

$$\delta x = \frac{4s}{x}\delta s \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

It should be noted that this last approximation is not usually permissible. It is, however, useful in that it gives the magnification in the zero position for an infinitely small displacement, namely

$$\frac{dx}{ds} = \frac{4s}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

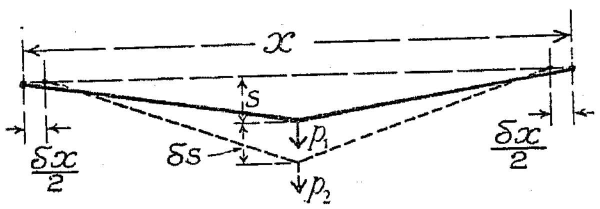

Fig. 9

(f) The Stress Limitation

The tension in the last stage of the magnifying system is equal to the tension in the fibre passing round the pulley on the spindle carrying the pointer multiplied by the magnification for infinitely small displacements from the zero position, as given by equation (17). The tension in the fibre cannot be indefinitely reduced, and the tension in the last stage cannot be indefinitely increased. There is thus a limit to the magnification quite irrespective either of the number of stages employed or of the quality of the zero-keeping considered desirable.

The tension in the last stage of magnification—or a multiple of it with the arrangement of Fig. 6—is applied directly to the hot wire and is in addition to the tension applied by the flexible end-cover of the tube. The two together must not give rise to a stress in the hot wire exceeding the limits stated on page 192. Since the moving systems are substantially the same in all the instruments, it follows that the stress limitation is most severely felt where the finest wires are used. The natural period of the pointer system must usually be longer in the low-current instruments for this reason. In the later designs embodying fine wires, a general lightening of the moving system has been attempted.

(g) Examination of a Magnifying System as actually Constructed

The dimensions of the magnifying system of the 4-ampere, 4-wire ammeter No. 11 are given in Fig. 6. The extensions of two wires are used, and the movement of the silk fibre over the pulley from zero to full load is 0·42 cm; the pull of the tensioning spring varying from 1 080 to 490 dynes. Preliminary calculation shows that in this system the elastic extensions are negligible.

For the first magnification (the "across" wires) $x = 4 \cdot 1$, $s = 0 \cdot 21$, and $p_1 = 1\,080$; whence $l = (4 \cdot 1 + 0 \cdot 0214)$ and $T_1 = 5\,300$ dynes. At full load, $s + \delta s = 0 \cdot 63$, whence $\delta x = 0 \cdot 172$ and $T_2 = 800$ dynes.

For the second magnification (the longitudinal wires) $x = 10 \cdot 2$, $s = 0 \cdot 81$, and $p_1 = 5\,300$; whence $l = (10 \cdot 2 + 0 \cdot 129)$ and $T_1 = 16\,800$ dynes. At full deflection, δs for each wire is one-half of the δx calculated for the first magnification, namely 0·086 cm. The corresponding δx for each of the longitudinal wires is then 0·026 cm.

There is an apparent magnification in the end covers of the tubes amounting to about 1·5, and the calculated extension of the hot wires to give the necessary full-scale deflection would thus be 0·017 as compared with the value 0·03 calculated from the mean temperature of the hot wire (see Table 5). The discrepancy is larger than would be expected and is certainly due to the fact that the end covers are distorted by the bending moment arising from the tension of the hot wire and the magnifying wire of the last stage. This bending moment is appreciably less in the position of full-scale deflection, and the straightening-out under the reduced load compensates to some extent for the extension of the hot wire. Calculations for other instruments having end covers to the tubes of the same shape show that this effect is common to all of them. This arrangement has not been used in the later design, partly for this reason and partly because supporting the cover from both sides as in Fig. 7 ensures a better centring of the hot wire in the tube and reduces the inductance of the end covers to a minimum.

The sagging wires are of phosphor bronze, and the diameter is 0·0036 cm for the first stage and 0·0071 cm for the second stage. The stresses are about 9×10^8 and $4 \cdot 6 \times 10^8$ dynes per cm^2 in the "across" and longitudinal wires respectively.

The load carried by each hot wire will be about 25 000 dynes. The cross-sectional area is $1 \cdot 65 \times 10^{-4}$ cm^2, and the stress in the wire is thus about $1 \cdot 5 \times 10^8$ dynes per cm^2, which is a very safe value.

It will be noticed that the arrangement of the magnifying system in this case is not ideal in that the "across" wire is shorter than the longitudinal wires, and yet the mid-point of the former moves through the greater distance from the no-load to the full-load position. If, however, the hot wires and their screening tubes are near together this arrangement is unavoidable. Moreover, the magnification for very small movements is much larger near the zero position than it is at the full deflection, a fact having an influence on the scale of the instrument since the decreasing amplification compensates to some extent for the intrinsic square law of the hot-wire principle.

(h) Effect of Temperature-change on Magnifying System

The change of temperature due to the energy expended in the instrument is very small (except in the hot wires), and temperature errors arise more from lack of zero-keeping when exposed to changing air temperature than from any difficulty in dissipating the watts lost in the hot wires. Should a rapid change of air temperature occur the frame of the instrument and the magnifying wires may differ in temperature temporarily.

From equation (16),

$$ds = \frac{x}{4s}dx$$

If the change, dx, arises from a difference of temperature, then dx varies proportionally to x and may be expressed as kx, where k is some very small fraction, being the difference between the coefficients of linear expansion of the materials of the wire and the base respectively, multiplied by the difference of their temperatures. The expression for ds thus becomes

$$ds = \frac{k}{4} \cdot \frac{x^2}{s}$$

With systems having constant magnification at the zero position but having varying lengths of wire, x/s is constant. With such systems, therefore, the sag due to difference of temperature will be proportional to x.

In order to avoid errors due to change of temperature it is thus desirable to use short magnifying wires adjusted to the appropriate initial sag, as determined by considerations of the tensions. This process cannot, however, be carried too far, since the initial sag must bear some reasonable relation to the change of sag required. Moreover, it is not practicable to attempt to give a very accurate small sag to a very short wire, and, if it is attempted, the effects of minute slipping at the joints of the wires become excessive.

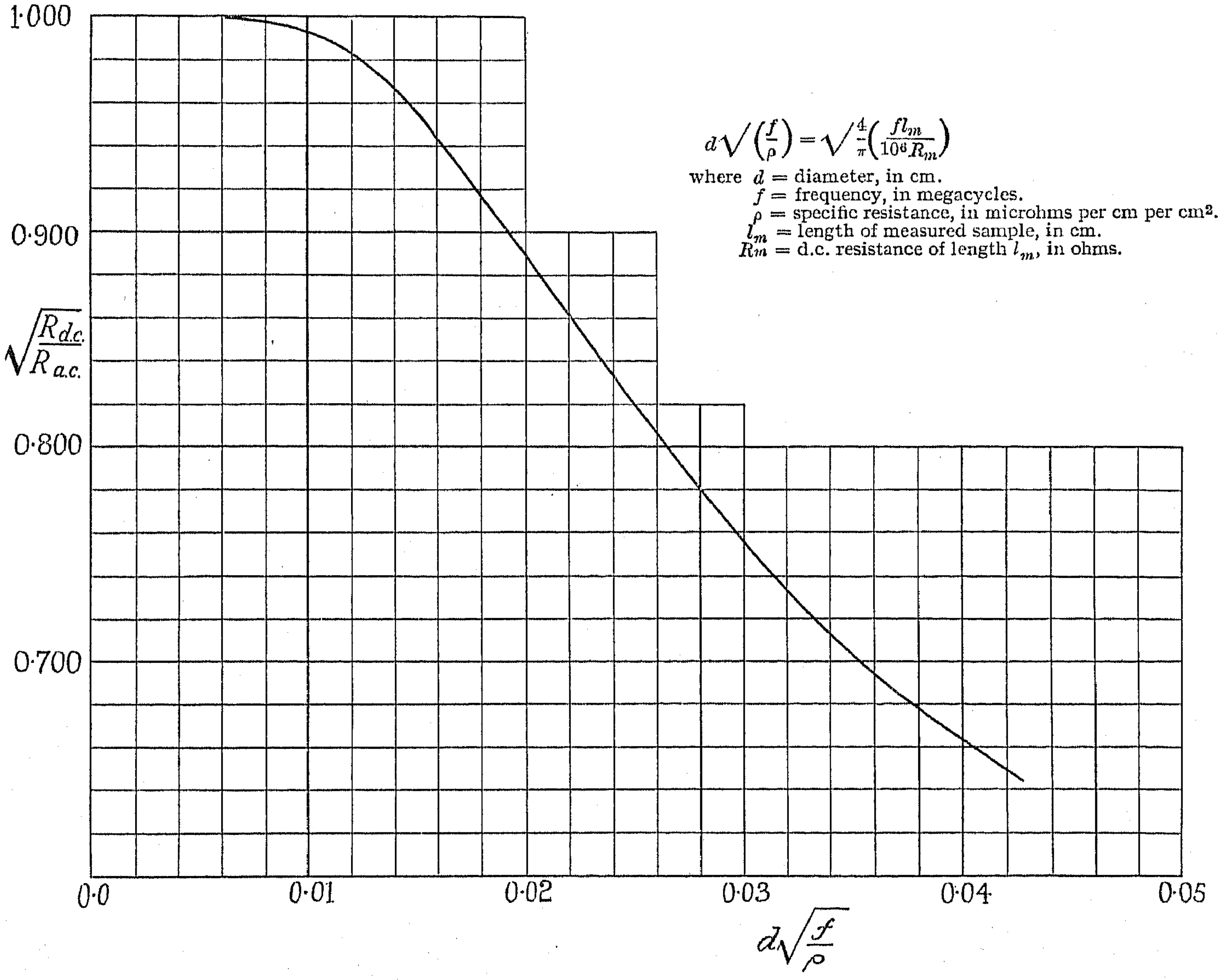

Fig. 10.—High-frequency resistance of cylindrical conductors.

(3) CORRECTION DUE TO CHANGE OF RESISTANCE OF HOT WIRES WITH INCREASE OF FREQUENCY

(a) Method of Calculating Correction

This was given in the earlier paper,* and involves only well-known principles. In working out the frequency correction the term involved is $\sqrt{(R_{d.c.}/R_{a.c.})}$, and it is convenient to plot this quantity directly in terms of $d\sqrt{(f/\rho)}$ as in Fig. 10; ρ here being in microhms per cm per cm^2. Some difficulty has been experienced in obtaining satisfactory values for $d\sqrt{(f/\rho)}$, owing to uncertainty with respect to the exact diameter of the wire, but if the value of ρ is obtained from the measured d.c. resistance, R_m, of a sample of wire of length l_m and diameter d, the exact measurement of d is unimportant. This follows because

$$\rho = R_m \cdot \frac{\pi}{4} \cdot \frac{d^2}{l_m} \cdot 10^6$$

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* *Loc. cit.*

and so

$$d\sqrt{(f/\rho)} = \sqrt{\left(\frac{4}{\pi}\,\frac{fl_m}{10^6 R_m}\right)}$$

and is thus independent of d.

The resistances of the inner surfaces of the screening tubes have not been comparable with the resistances of the wires in any instruments yet made.

(b) Equal Distribution of Current in Multi-wire Instruments

Any lack of equality in the impedance of individual wires of an instrument would cause the current to have a distribution at high frequency different from the distribution with the calibrating direct current. Equality of distribution under both conditions is ensured by measuring the length, diameter, and resistance, of each individual wire before it is inserted in the instrument; and then measuring the resistance between terminals as each wire is put in. If the resistances are equal before mounting, and if the resistance between the terminals falls by the correct fraction as each wire is put in, it follows that the calibrating direct current will be equally distributed. If the length and diameter of the wires are the same for all, the inductance will be the same, and this alone is sufficient to ensure that the high-frequency current will be equally divided between the wires, quite irrespective of any small discrepancies in the high-frequency resistance. It seems unlikely, therefore, that any error can arise from this source. Moreover, careful comparisons of ammeters designed for the same full-load current but having different numbers of wires and wires of different diameters, have shown agreement within the limits of accuracy with which they can be compared.

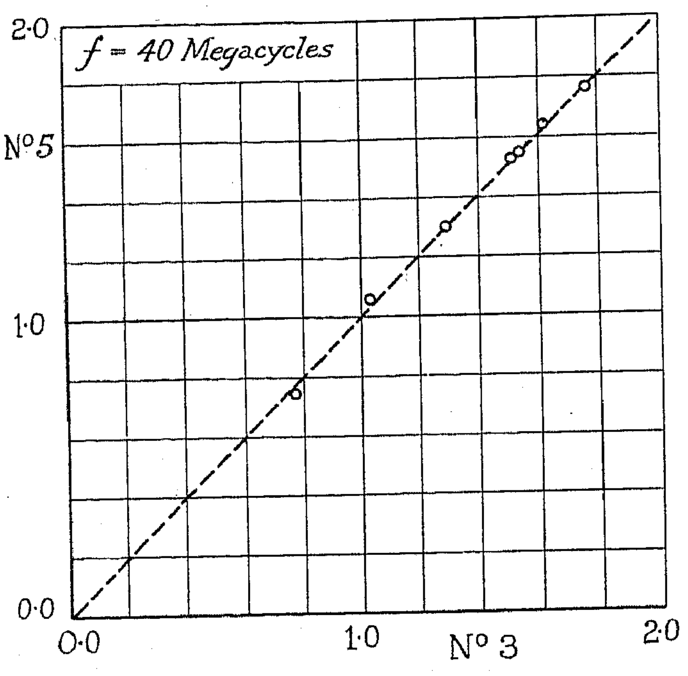

Fig. 11.—Graph representing comparison of instruments Nos. 3 and 5.

Fig. 11 relates to an early comparison of two instruments, Nos. 3 and 5, each designed for a maximum current of 2·0 amperes. Ammeter No. 3 then had two hot wires in parallel, each 7·55 cm long and of reputed diameter 0·014 cm; whereas ammeter No. 5 had four wires, each 10·2 cm long and of reputed diameter 0·0076 cm. The correction factors for these two instruments are given in Fig. 12, and it will be observed that they differ widely. The technique followed in carrying out these comparisons has been described elsewhere.*

(c) Effect of Imperfect Wave-form

The ratios $R_{d.c.}/R_{a.c.}$ calculated from the ber and bei series relate to sinusoidal currents. The results are, however, also applicable to currents of imperfect wave-form, because for any superimposed harmonic systems of currents the total losses will be the sum of the losses due to the two systems separately.

Suppose the current to be

$$i = i_1' \sin \omega t + i_n' \sin n\omega t$$

The r.m.s. values of the fundamental and harmonic are $I_1 = i_1'/\sqrt{2}$ and $I_n = i_n'/\sqrt{2}$ respectively, and the true r.m.s. value of the current i is $I = \sqrt{(I_1^2 + I_n^2)}$. The alternating-current resistance may be expressed as $R_{a.c.} = r_1 R_{d.c.}$ for the fundamental and $R_{a.c.} = r_n R_{d.c.}$ for the harmonic; where r_1 and r_n can be found from Fig. 10 for any particular case.

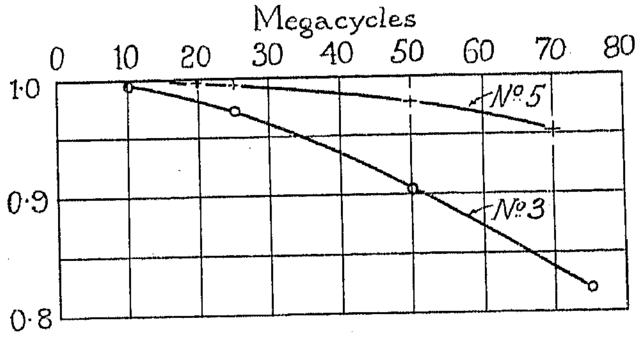

Fig. 12.—Correction factors for instruments Nos. 3 and 5.

The actual losses in the hot wire will be given by

$$R_{d.c.}(r_1 I_1^2 + r_n I_n^2)$$

Thus, if $I_{d.c.}$ is the calibrating current which gives rise to the same increase of temperature,

$$I_{d.c.}^2 = r_1 I_n^2 + r_n I_n^2 \quad . \quad . \quad . \quad . \quad (18)$$

Now let $i_0 = i_0' \sin \omega t$ be the sinusoidal current of only the fundamental frequency which causes the same temperature-rise. Then the r.m.s. value is $i_0'/\sqrt{2} = I_0$, and

$$I_{d.c.}^2 = r_1 I_0^2 \quad . \quad . \quad . \quad . \quad . \quad (19)$$

This value of I_0 is the value which would be derived from the indication of the instrument and the correction factor for only the fundamental frequency.

The true r.m.s. current is $\sqrt{(I_1^2 + I_n^2)}$, and the ratio $I_0/\sqrt{(I_1^2 + I_n^2)}$ gives a measure of the inaccuracy introduced by neglecting the added loss due to the presence of the harmonic. From equations (18) and (19), however,

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* *Journal of Scientific Instruments*, 1931, vol. 8, p. 94.

$$\frac{I_0}{\sqrt{(I_1^2 + I_n^2)}} = \sqrt{\left[\frac{I_1^2 + (r_n/r_1)I_n^2}{I_1^2 + I_n^2}\right]} = \sqrt{\left[\frac{1 + (r_n/r_1)(I_n/I_1)^2}{1 + (I_n/I_1)^2}\right]}$$

If $(I_n/I_1)^2$ is small, this ratio becomes

$$1 + \tfrac{1}{2}\left(\frac{I_n}{I_1}\right)^2 \left(\frac{r_n}{r_1} - 1\right) \quad . \quad . \quad . \quad . \quad (20)$$

and the second term in this equation is a measure of the error involved in neglecting the presence of the harmonic.

For example, suppose that in a particular case the value of $d\sqrt{(f/\rho)}$ for the fundamental frequency is 0·02. The value of r_1 derived from the curve of Fig. 10 is $1/(0 \cdot 888)^2 = 1 \cdot 294$. For the second harmonic the corresponding value of $d\sqrt{(f/\rho)}$ is 0·0283, and the value of r_n is $1/(0 \cdot 775)^2$. Thus $(r_n/r) - 1 = 0 \cdot 29$. For a second harmonic of amplitude 20 per cent that of the fundamental, the value of $(I_n/I_1)^2$ is 0·04 and the percentage error arising from the neglect of this harmonic is $0 \cdot 29 \times 0 \cdot 04 \times 100 = 1 \cdot 2$.

Thus, so far as change in resistance is concerned, the error due to the presence of harmonics is generally not serious. The only conditions when errors of large magnitude are to be expected are when there are large harmonics of high multiple frequency. For fundamental frequencies of from 25 to 75 megacycles, such harmonics may possibly exist in some cases, but probably not often. Second harmonics undoubtedly occur frequently, but, as shown above, serious errors are not involved unless the magnitude of the harmonics exceeds 20 or 25 per cent of the fundamental; a state rarely found in practice.

(d) Variation of Correction Factor with Current Amplitude

As shown in Section (3) (*a*), the value of $\sqrt{(R_{d.c.}/R_{a.c.})}$ is dependent upon the measured resistance R_m, which may vary by as much as 6 per cent from full current to zero current. The maximum change in $\sqrt{(R_{d.c.}/R_{a.c.})}$ consequent upon this may be estimated from the maximum slope of the curve of Fig. 10, and is about 4 per cent. These ammeters are not often used at less than half full-load current, and the correction factors have usually been calculated and recorded on the instruments for full-load conditions. For the highest accuracy, allowance must be made for the change of resistance by calculating correction factors for full load, three-quarters full-load and half full-load, and using whichever is appropriate to the particular circumstances.

(e) The Inductive Shunt

The impedance of these instruments is inductive, and the power factor is low. If, therefore, they are shunted by a circuit of a similar quality, the division of the high-frequency current between the hot wire and the shunt is determined by the relative inductances and is substantially independent of frequency. For example, a 1-ampere, single-wire instrument may have an inductance of about 0·05 μH, depending upon the length of wire used. To convert this to a 10-ampere instrument, a shunt of inductance about 0·0055 μH would be necessary. A solid copper rod 5 mm in diameter and about 4 cm long, mounted in a coaxial cylinder of 1-cm bore, has approximately this inductance and could be used in this way to extend the range of the original instrument.

It appears at first sight that the correction factors of instruments of this type could be calculated as accurately as those of the ordinary single- or multi-wire instruments, and that if they could be calibrated with direct current with the inductive shunt disconnected, an exact multiplier could be obtained which would enable the r.m.s. value of the alternating currents to be found when the shunt is in use. If this were possible, the shunted instruments would constitute as accurate a transfer from direct current to alternating current as the single- or multiple-wire instruments. Unfortunately a difficulty arises owing to the inductance of the high-tension terminal itself. The distribution of current over the terminal cannot be known exactly, and this introduces the possibility of errors amounting to several per cent. Nevertheless, one instrument has been constructed with a hot wire carrying 0·33 ampere and a shunt carrying 3·66 amperes. This is arranged so that the shunt can be disconnected and a direct-current calibration of the hot wire taken. The dimensions are such that there is a multiplier of 12 in virtue of the shunt; to which must also be applied the frequency correction for change of resistance of the hot wire. The effect of the terminal capacitance is negligible. Careful comparisons of this instrument with a 4-wire 4-ampere instrument have not yet been possible.*

(4) CALCULATION OF COMPLETE CORRECTION FACTOR AND OF IMPEDANCE OF INSTRUMENTS

(a) Complete Correction Factor

This is also given in full in the earlier paper.† The approximations leading to equations (8) and (9) of that paper have always been found to be satisfied. The correction due to the terminal capacitance is in general negligible for frequencies below 50 megacycles.

(b) Effect of Inductance of End Covers of Screening Tubes

In the previous calculations it was assumed that the hot wire was short-circuited to the screening tube at its farther end. This assumption is not quite justified, since the flexible end-cover always has a small inductance. The value of this is difficult to measure, and can only be approximately calculated by making somewhat arbitrary assumptions with respect to the magnetic field associated with the current in the end covers. For example, one arrangement of the flexible cover is as shown in Fig. 13.

A rough estimate gives $L = 10^{-9}$ henry. The inductance of the hot wire is, in this case, about 17×10^{-9} henry. The effect of the inductance of the end covers is thus to increase slightly (in this case by about 1 in 17) the current flowing in the terminal capacitance. This latter is almost negligible in all cases, and although every effort is made to keep the inductance of the end covers as low as possible, no serious attempt has been made to measure or calculate it exactly.

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* Later experiments have shown that the terminal inductance introduces an error of about 6 per cent.

† *Loc. cit.*

(c) The Scales of the Instruments

It was proposed in the earlier paper to prepare for these ammeters scales embodying the frequency corrections directly, and this was actually done in the first instance (as shown in Fig. 3 of that paper). Subsequently, however, it was found more convenient to give the direct-current calibration on the scale in the ordinary

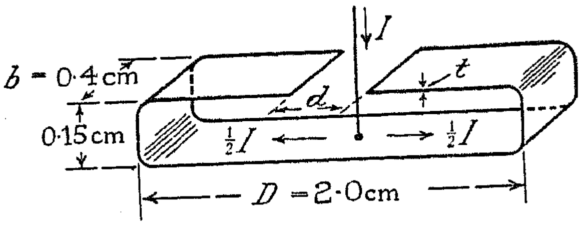

Fig. 13

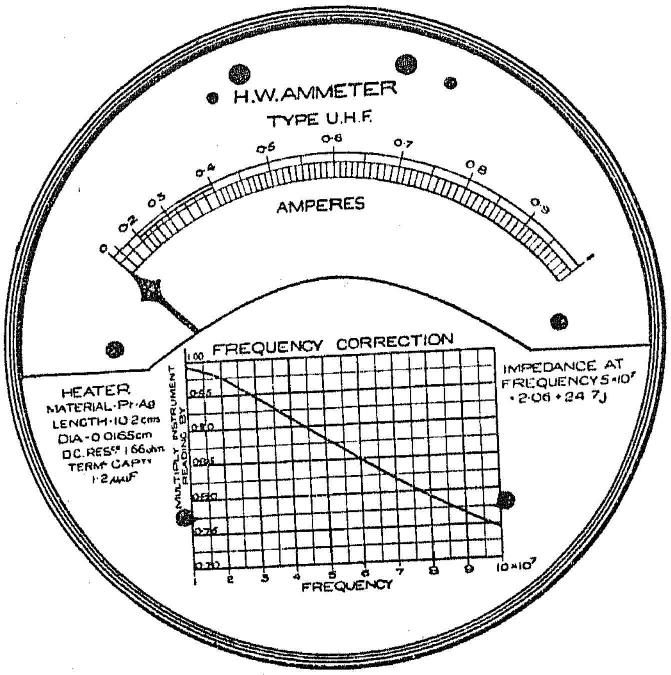

Fig. 14

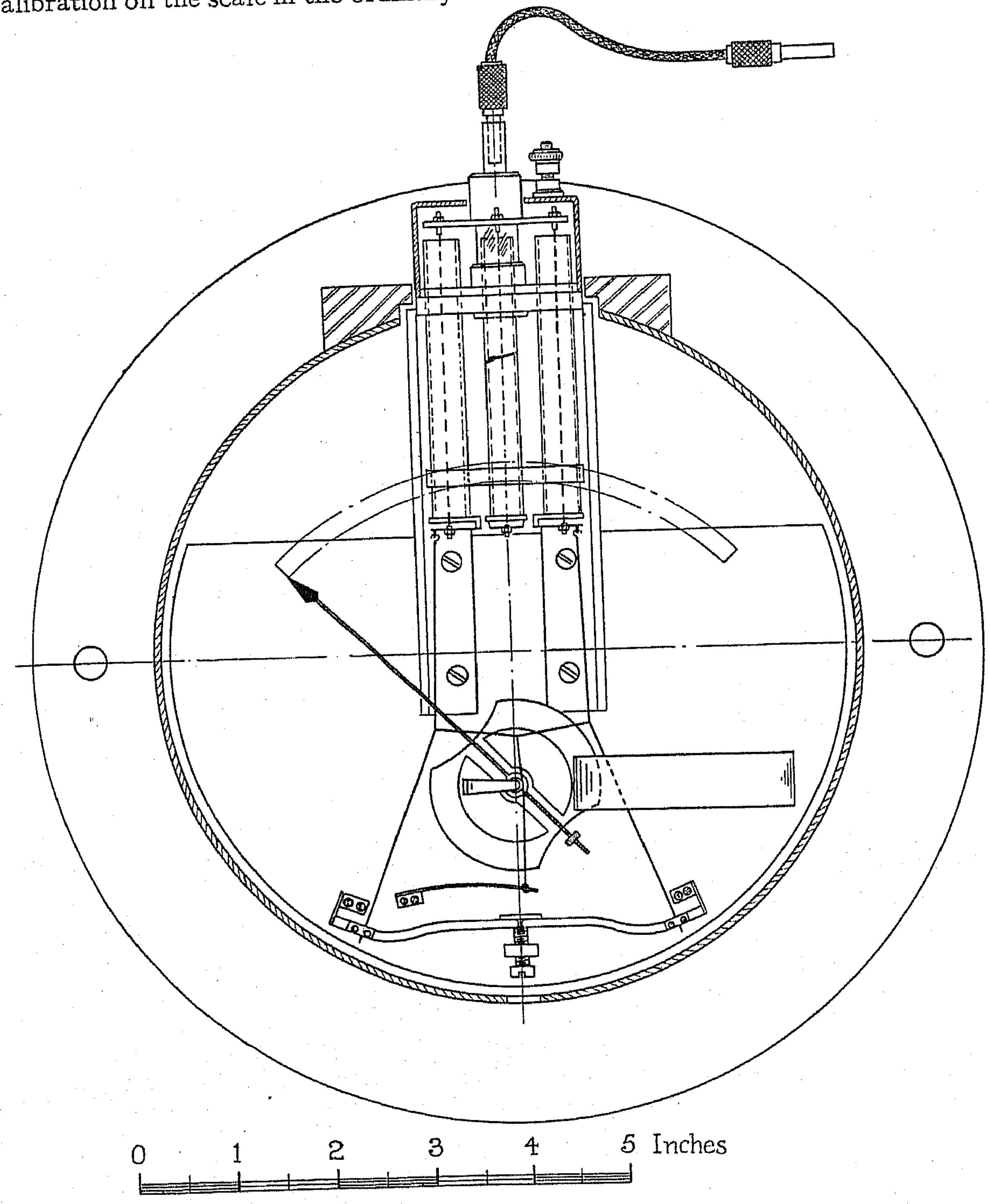

Fig. 15

way, and to make use of a small graph mounted adjacent to the scale and giving the correction factor in terms of the frequency. This has the advantage that the instrument can be calibrated by the makers in the ordinary way and the curve of the correction factors can be prepared independently when full information is available with respect to the mechanical and electrical details. Fig. 14 shows the scale and the curve of correction factors for a particular instrument.

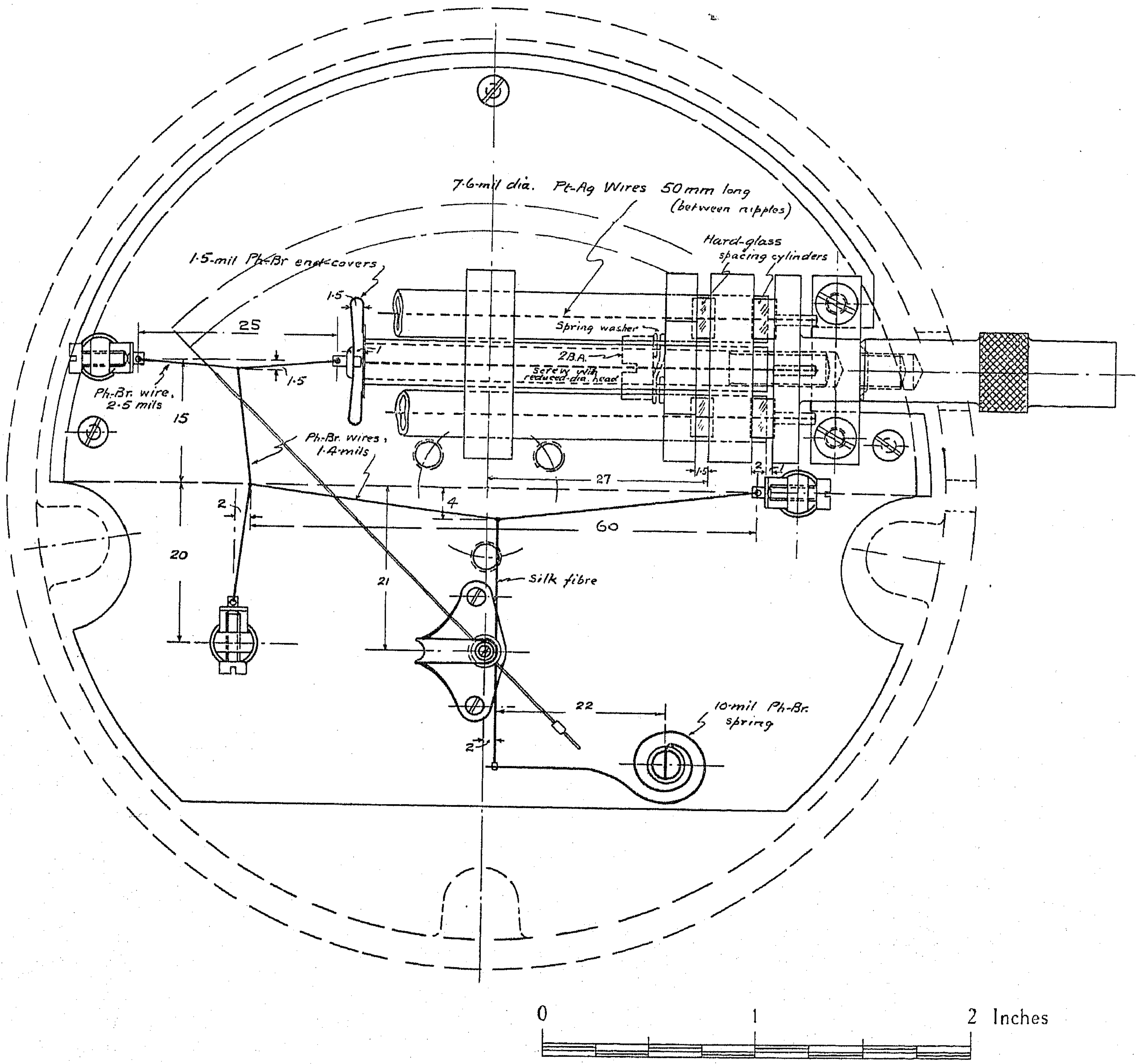

Fig. 16

(5) MECHANICAL DETAILS OF CONSTRUCTION

(a) Improvements on Original Design

The general tendency has been in the direction of shortening both the hot wires and the magnifying system, rendering them symmetrical, and including everything but the high-tension terminal within the case of the instrument. In the latest designs this process has been carried to the extreme limit and even the high-tension terminals are enclosed, connections to them being made by means of terminals inserted through small doors at the side.

Fig. 15 shows the general arrangement of one form of multi-wire instrument, the hot wires being 7·5 cm long. Fig. 16 shows the arrangement of a more compact 3-wire 3-ampere ammeter in which the hot wires are 5·0 cm long. Both of them are arranged—purely as a matter of convenience—to use the standard moving system, base, and cover, of a well-known make of hot-wire ammeter.

(b) Mounting the Hot Wires

Experience has shown that it is not satisfactory to use ordinary solder with the platinum-silver alloy, and the joints are now made by brazing the wire into small brass nipples with a silver-alloy brazing material. The nipples may be threaded and held in position in the ammeters by nuts at each end, or they may be soft-soldered, care being taken that the solder does not come into contact with the platinum-silver wire. The arrangement of a wire with two nipples and nuts and of a wire with a nipple for soldering are shown in Fig. 17. The brazing presented great difficulties owing to the tendency to melt the fine wire and on account of the necessity of having the wires accurately of the required length. The process finally adopted was to drill a fine hole throughout the length of each nipple and to arrange both wire and nipple in such a way that after the nipple and brazing material have been sufficiently heated in a fine gas flame, the latter is removed and, simultaneously, the wire advanced the required distance into the nipple. This device protects the wire, and, by the use of appropriate adjustable stops on the mechanism advancing the wire, a high degree of equality in the lengths of the wires is obtainable.

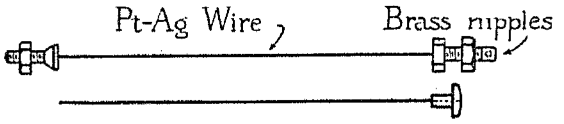

Fig. 17

(c) Mechanical Properties of Platinum-Silver Wires

Platinum-silver alloy does not appear to be extensively used, and there is little exact information available with regard to it. It can be drawn fairly accurately to reputed size, as shown by the measurements given in Table 6.

Table 6

Reputed diameter	Mean observed diameter of several samples
cm	cm
0·01622	0·01588
0·01395	0·01360
0·01016	0·00998
0·00762	0·00787
0·00633	0·00647

The wire is supplied by the manufacturers in a hard-drawn state, and its ultimate breaking strength in this state is given in the International Critical Tables as 80×10^8 dynes per cm². Tests of pieces of wire of about 2·5 cm length, brazed into nipples by the procedure described above, gave the following mean results: Measured diameter 0·00787 cm, ultimate strength 62×10^8 dynes per cm²; measured diameter 0·01588 cm, ultimate strength 54×10^8 dynes per cm². The fractures were near the nipples in all cases.

Samples of the wire were also tested with gradually-applied loads, the extension being observed by means of measuring microscopes at each end. This arrangement was used to obviate any possibility of error due to slipping at the point of attachment. For loads up to the ultimate breaking strength there is no observable elastic limit, or any point at which noticeable plastic extension occurs. For loads up to 60 per cent of the elastic limit the extension/load curves repeat exactly within the limits of accuracy of the readings on the eyepiece scales of the microscope. The value of Young's modulus given by these tests is about $0{\cdot}9 \times 10^{12}$ dynes per cm².

No fatigue tests have been possible, and there is thus no information available as to the behaviour of the material in this respect. The conditions prevailing in the ammeters do not vary very rapidly except when the instruments are being moved and the pointer system set swinging to and fro about the zero position.

As far as can be judged from the observed properties of the material, a stress of 10×10^8 dynes per cm² is thus a safe value, and if necessary this figure could be increased to 20×10^8 without probability of failure. Taking the lower value of 10×10^8 dynes per cm², Table 7 gives the loads which could be carried by the five wires of Table 6.

Table 7

Reputed diameter	Actual diameter	Safe load at zero reading
in.	cm	dynes
0·0064	0·01588	198 000
0·0055	0·01360	145 000
0·0040	0·00998	78 000
0·0030	0·00787	48 000
0·0025	0·00647	33 000

(d) Flexible End-covers

These are of phosphor bronze, the breadth and thickness of those shaped as shown in Fig. 15 being calculated from the expression

Deflection, in cm

$$= \frac{T_c}{16Ebt^3}\left[\frac{(2D^2 - d^2)^2 - 8Dd(D-d)^2}{2D - d}\right]$$

where T_c is the tension in the wire to be exerted by the end cover, E is Young's modulus, and b, t, D, and d, are the dimensions shown in Fig. 13.

(e) Magnifying Wires

Phosphor-bronze wires of diameter 0·0076 cm and 0·0036 cm have been found satisfactory. In the hard-drawn condition these wires will carry loads of approximately 10^5 dynes and 2×10^4 dynes respectively, the stresses being thus about 20×10^8 dynes per cm².

The method of attaching the magnifying wires to the end covers of the screening tubes must be such that there is no tendency to slip and so cause gradual change of zero. At the same time the wire must be held in such a way that it is not damaged, and so that it can be easily removed when new hot wires are required. Soldering has not proved satisfactory, and the method now used is that shown in Fig. 18. The end of the wire is threaded through a short length of fine silver tube, and the end is silver-soldered. The tube and wire are then bent round into a small slightly angular hook, which engages with an eye on the end cover of the screening tube. Wires mounted in this way have been tested to destruction, and the behaviour of the joint observed by means of a measuring microscope. No measurable creep has been found to occur.

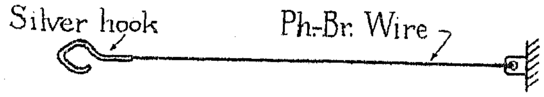

Fig. 18

This construction is now used at both ends of the heavily loaded wires attached to the end covers of the tubes. The more lightly loaded cross-wires are bent completely round the mid-points of the wires to which they are attached, and soft-soldered with a fine soldering bit.

The silk fibres passing round the pulley of the moving system are attached by means of shellac both to the wires and to the controlling spring. The fibre has usually been passed twice round the pulley in a V-groove; the mid-point being anchored by a small set-screw.

Various means have been adopted for making up the magnifying systems. They are generally adjusted approximately and then soldered in position. The sag is then corrected by means of screw adjustment to the magnifying wires or to the tensioning spring. Jigs could no doubt be devised to enable the magnifying systems to be made up rapidly and easily, but these have not so far been used.

(f) Moving System

A standard movement mentioned above has been used in all but one ammeter, with or without the magnetic damping device.

ACKNOWLEDGMENTS

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The author is indebted to many members of the staff of the Electrical Department of the College—notably Mr. C. R. Urwin—who have given extensive assistance. He is also indebted to his son, Mr. R. L. Fortescue, who undertook a very careful comparison of several instruments at an important juncture when the possibility of serious error had arisen.

[The discussion on this paper will be found on page 200.]

AN IMPROVED FORM OF RESPONSE-CURVE PROJECTION APPARATUS

By D. G. REID, B.Sc.(Eng.), Associate Member.

(*Paper received* 13*th July*, 1935; *read before the* WIRELESS SECTION 1*st April*, 1936.)

SUMMARY

The paper describes a combination of beat-frequency oscillator and cathode-ray oscillograph so arranged that the oscillator output is rapidly varied in frequency over a limited range without appreciable change in amplitude, and, after passing through the apparatus whose response curve is to be measured, is applied to the vertical deflector plates of the oscillograph, the horizontal deflection being proportional to the frequency.

A frequency scale is obtained on the oscillograph by means of piezo-electric crystals, so that the calibration of the instrument is unaffected by variations in supply voltages, etc.

The variation of frequency is obtained by electrical means instead of by the usual rotating condenser, and the absence of mechanically moving parts renders the apparatus compact and portable.

(1) INTRODUCTION

The delineation of frequency response curves of electrical and acoustic circuits is a matter which is frequently of importance in investigations on such circuits. The conventional point-by-point method is quite satisfactory where only a few such investigations are to be made, but becomes tedious when the number is large. An example which may be instanced is the routine testing of the intermediate-frequency amplifier stages of broadcast receivers. Apparatus which will give a picture of the complete frequency response curve saves a considerable time in the final testing, besides allowing the effect of adjustments in tuning, etc., to be instantly visible. One form of such apparatus has already been described;* it consists of a valve oscillator the frequency of which is varied by a rotating condenser, a valve rectifier, and a multi-stage battery-coupled amplifier operating a Duddell oscillograph. Similar forms of such apparatus, but employing a cathode-ray oscillograph in place of the Duddell type, are in use by various radio-receiver manufacturers for routine testing, a particular example having been recently described elsewhere.†

The apparatus described below differs from the foregoing in the following particulars:—

(i) The variation in frequency is obtained electrically, from a conventional linear time-base or any other source of low-frequency oscillation, without the use of mechanically moving parts. The consequent absence of sliding contacts is an obvious advantage, and, moreover, the cathode-ray oscillograph is especially adapted to an electrical rather than a mechanical means of frequency variation. With a string oscillograph, the converse is true.

(ii) The oscillator is of the heterodyne or beat-frequency type. Thus the mid-frequency of the band of frequencies produced may be rapidly varied over a very large frequency range without varying the band width and with only slight alterations to the tuning adjustments. The band width is also variable by controlling the amplitude of the voltage from the time-base, without affecting the mid-frequency.

(iii) By an arrangement of two or more quartz crystals, a frequency base is delineated directly on the screen of the cathode-ray oscillograph. The separation between two vertical lines traced out by the oscillograph denotes a frequency interval of 12·5 kilocycles per sec., which is independent of the band width and mid-frequency.

(2) DESCRIPTION OF APPARATUS

(a) General

A complete circuit diagram of the apparatus is shown in Fig. 1. Indirectly-heated a.c. valves are used throughout, the cathodes being directly earthed in all cases. Careful shielding and decoupling arrangements are employed to prevent interaction between various parts of the circuit.

The circuit consists basically of a heterodyne oscillator, the two oscillator valves which beat together being indicated by V_2 and V_4. The frequency of oscillation of V_4 is adjustable by means of the condenser C_4, and determines the mid-frequency of the band. The frequency of oscillation of V_2 is determined partly by C_2, which is variable within narrow limits, and also, in a manner described in the next Section, by the bias on the grid of V_1, which in turn is driven by the time-base. Thus the frequency of V_2 sweeps over a range from, say, f_1 to f_2 at a rate dependent on the speed of the time-base, whilst that of V_4 remains constant at, say, f.

The output from V_2 is amplified by the screen-grid valve V_3, the major function of which is to act as a buffer valve rather than to amplify, and, after passing through the coupled circuits C_3L_3–C_6L_6, whose double-humped response curve is so arranged as to cover the range of frequencies from f_1 to f_2, is fed to the first grid of the modulator heptode V_7.

The output from V_4 is similarly amplified by V_5, a single resonant circuit C_5L_5 here being sufficient, as only one frequency is handled at any particular setting. The selectivity of C_5L_5 is made as high as possible, to suppress the harmonics of f which would give rise to spurious

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* C. L. FORTESCUE and F. RALPH: "Response Curves of Electrical Circuits," *Journal I.E.E.*, 1930, vol. 68, p. 583.

† R. F. PROCTOR and M. O'C. HORGAN: "Oscillographic Response-Curve Examinations," *Wireless Engineer*, 1935, vol. 12, p. 363.

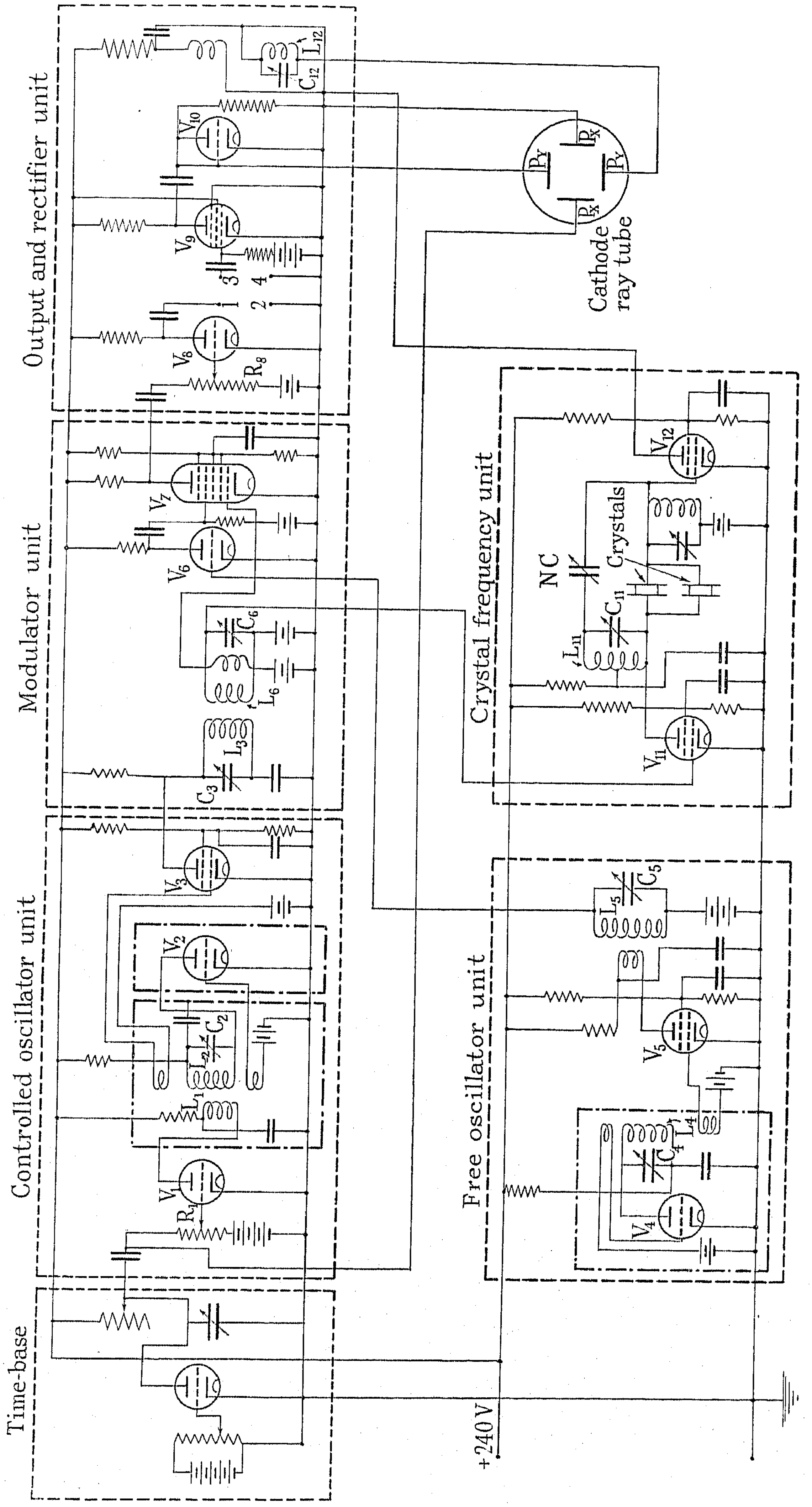

Fig. 1.—Circuit diagram of response-curve projection apparatus.

Tinned-iron dust-cover screens shown thus: – – – – – –
Copper screening boxes shown thus: ▬ ▪ ▬ ▪ ▬

beat-frequencies in the later stages. The tuning range of the C_5L_5 circuit is of course the same as that of C_4L_4.

The output from C_5L_5 is applied to the grid of the low-impedance triode V_6, whose anode is coupled through a low resistance to the fourth or signal grid of the heptode V_7. The function of V_6 is to eliminate the electron coupling which would otherwise occur between the first grid of V_7 and the C_5L_5 circuit. It was found that in the absence of such separation a large voltage having the frequency of the oscillator V_1 was set up on the fourth grid of V_7 when C_5L_5 was tuned to a frequency near the range from f_1 to f_2. Such a voltage reduced the conversion conductance of V_7, with the result that the beat-frequency output from the latter varied in magnitude in an undesirable manner as the frequency of V_1 swept over the range from f_1 to f_2. By the use of the low-resistance coupling between V_6 and V_7, the magnitude of this electron-coupling voltage is decreased; it is approximately constant over the whole frequency range.

The anode current of V_7 contains components of frequencies varying between $(f_1 - f)$ and $(f_2 - f)$, and in addition an upper "side-band" from $(f_1 + f)$ to $(f_2 + f)$. The latter is an unwanted component, but, with the frequencies used, it is at least 6 times the highest frequency in the required lower side-band. There are also present components of the original input frequencies, from f_1 to f_2 and f, together with their harmonics, but it is found that the capacitance to earth of the wiring between V_7 and V_8 is sufficient to bypass all but the required lower side-band components, and a low-pass filter following V_7 was found to be unnecessary.

The output from V_7 is applied to the circuit whose response curve is to be measured, the output from the circuit being applied to the grid of the pentode V_9. The amplified output from this valve is rectified by the diode V_{10} and applied to the vertical deflector plates of the cathode-ray oscillograph. The horizontal deflection is proportional to the voltage on the grid of V_1, which directly controls the frequency.

The crystal frequency-base unit consists essentially of a highly selective amplifier, responsive to two frequencies 12·5 kilocycles per sec. apart and lying within the range f_1 to f_2. As the frequency of V_1 sweeps over these two frequencies in succession, two "bursts" of high-frequency current are induced in the flatly tuned resonant circuit $L_{12}C_{12}$ in the vertical deflector-plate circuit of the cathode-ray tube. Two thin vertical lines are thus produced on the cathode-ray screen, in addition to any deflection which may be present due to rectified voltage from V_{10}; and the separation between these lines represents a 12·5-kilocycle interval.

(b) Frequency-Control Principle

The method of controlling the frequency of V_2 by the bias on V_1 depends on the fact that the reactance of a coil L_2, to which is coupled a coil L_1 and resistance R_1 [Fig. 2(*a*)], is given by the expression

$$X_{L_2} = j\omega\left(L_2 - \frac{\omega^2 M^2 L_1}{R_1^2 + \omega^2 L_1^2}\right)$$

where M is the mutual inductance between L_1 and L_2. Now if the coil L_2 forms the inductive branch of the resonant circuit L_2C_2 of a valve oscillator, oscillation will take place at such a frequency that the total reactance around the series circuit L_1C_1 is zero, or very nearly so. That is

$$\frac{1}{\omega C_2} = \omega\left(L_2 - \frac{\omega^2 M^2 L_1}{R_1^2 + \omega^2 L_1^2}\right)$$

To obtain an explicit solution for ω, put $\omega_1 = 1/\sqrt{(L_2C_2)}$, the pulsatance in the absence of control (i.e. when R_1 is infinite); $k = M/\sqrt{(L_1L_2)}$, the coupling coefficient between the coils; and $x = R_1/(\omega_1 L_1)$. Then

$$\omega = \omega_1\sqrt{\left\{\frac{(1-x^2)^2 + \sqrt{[(1-x^2)^2 + 4(1-k^2)x^2]}}{2(1-k^2)}\right\}} \quad (1)$$

Thus variation of R_1 may be used to control the frequency of oscillation.

In this apparatus, the place of R_1 is taken by the anode-filament resistance of the control valve V_1, the value of which is controlled by the anode and grid potentials. Now it is a requirement of the apparatus that the frequency shall be proportional to the grid bias on the control valve. It appeared somewhat unlikely that a combination of the non-linear expression above and the non-linear relationship between anode resistance and grid bias would give the required linear relation between frequency and bias. Fortunately, however, it did not prove difficult to find a combination of anode and grid voltage to give such a result over a limited range of frequencies.

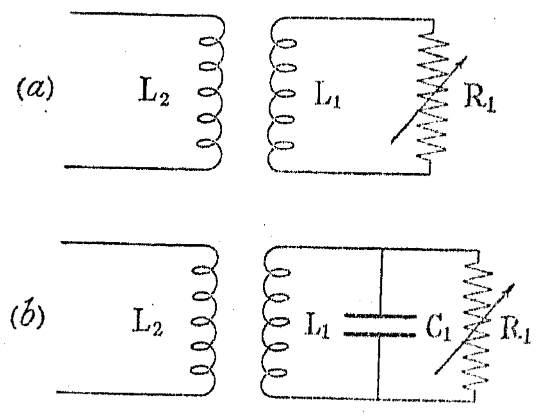

Fig. 2

In the original design of the apparatus a frequency band of 20 kilocycles per sec. was aimed at, and, since it was anticipated that difficulty might be experienced in obtaining a linear frequency/bias relation over a large percentage change of frequency, the uncontrolled frequency of V_2 was set at approximately 1 700 kilocycles per sec., so that a 20-kilocycle band represented a change of only just over 1 per cent. The coupling between the two coils was made as close as possible, consistent with capacitance effects at this frequency, but even so the measured coupling coefficient (k) was only 0·24. The measured values of L_1 and L_2 (see Fig. 1) were 172·3 and 93·2 microhenrys respectively, and the operating frequency with V_1 removed was 1 770 kilocycles per sec. Using expression (1), the operating frequency for various resistances across L_1 was calculated and also measured experimentally, the results being shown in curves (*a*) and (*b*) respectively, Fig. 3. The discrepancy between the observed and calculated results is chiefly accounted for by the effects of the capacitance C_1 across L_1 [Fig. 2(*b*)], which represents the combined effects of valve inter-electrode capacitance and the self-capacitance of the coil L_1. An exact expression for the frequency, taking this capacitance into account, is difficult to use, as it involves the roots of a quartic equation, but an approximate expression is as follows:—

$$\omega = \omega_1\sqrt{\left\{\frac{(1 - a^2x^2) + \sqrt{[(1 - a^2x^2)^2 + 4a^2x^2(1 + ak^2x^2 - a^2k^2x^2 - k^2)]}}{2(1 + ak^2x^2 - a^2k^2x^2 - k^2)}\right\}}$$

where ω_1, k, and x, have taken the same significance as in (1), and

$$a = 1 - \frac{L_1C_1}{L_2C_2}$$

Assuming a value for C_1 of 10 $\mu\mu$F, curve (*c*) of Fig. 3 was obtained by calculation, and is seen to be in fairly close agreement with the experimentally-obtained curve over a fairly wide range of resistance. In fact, the remaining discrepancy can be largely accounted for by the inherent resistance of the coil L_1, the effect of which would be to displace the calculated curves (*a*) and (*c*) in Fig. 3 to the right. The effect of capacitance shunting L_1 is thus to increase the percentage change in frequency for a given change in resistance. Too large a capacitance has been found by experiment to produce unstable operation and discontinuities in the frequency/resistance curve, in the manner of the well-known *Ziehen* effect.

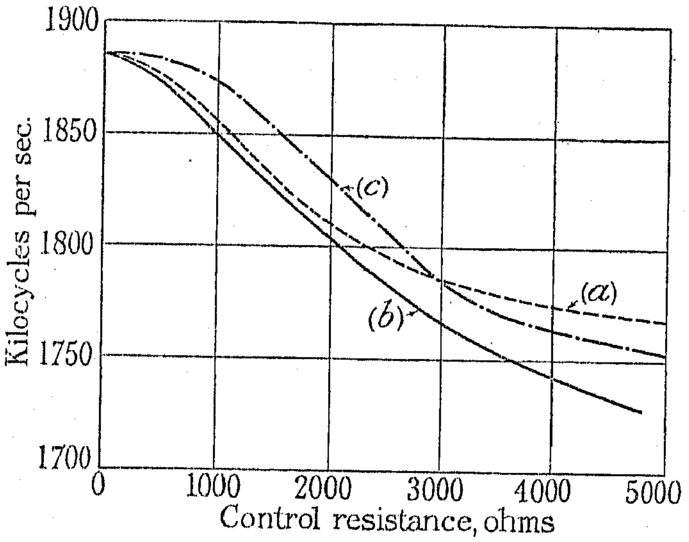

Fig. 3

It will be noticed that the maximum frequency-control effect occurs over a range of resistance from approximately 1 000 to 3 000 ohms, a range over which the anode impedance of a normal receiving output valve may conveniently be varied. A curve is given subsequently (Fig. 4) showing the relationship between frequency and grid bias on the control valve V_1.

The method of frequency control outlined above has been used previously* in connection with the synchronization of a local oscillator with a pilot signal.

(c) Amplitude Equalization

The reflection of negative reactance into the oscillatory circuit according to equation (1) is accompanied by the reflection of positive resistance, with the result that changes in frequency of oscillation of V_2 are accompanied by changes in amplitude. As it is desired to produce at the terminals 1, 2 (Fig. 1), a voltage of variable frequency but constant amplitude, the coupled circuits C_3L_3–C_6L_6 are so adjusted that the frequency-range covered by V_2 falls on the side of the resonance curve, with the result that the voltage on the first grid of V_6 is substantially constant. The exact adjustment of C_3L_3 and C_6L_6 is found by experiment, and is rather critical. It is probable that the double-humped resonance phenomenon previously mentioned is masked by the mistuning of the two circuits, with the result that a single asymmetrical resonance curve is produced, with a substantially straight, sloping top. Since the voltage from the free oscillator V_4 is constant for any given position of the frequency band in the spectrum, the amplitude of the beat-frequency component in the anode current of V_6 is constant over the band. In order to maintain this constancy in the voltage produced at the terminals 1 and 2, the coupling resistances in the anode circuits of V_7 and V_8 are kept small (6 000 ohms and 2 000 ohms respectively).

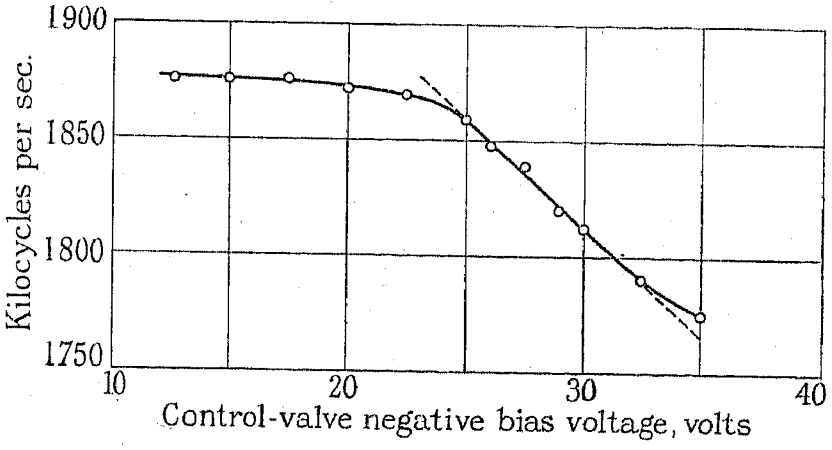

Fig. 4.—Variation of controlled valve-frequency with control-valve bias.

(d) Frequency Range

The apparatus is designed to cover a frequency range from 0 to 500 kilocycles per sec., the upper frequency limit being determined by considerations of separating the beat from the beating frequencies. The lower limit was found in practice to be about 100 cycles per sec., and was determined by (i) the frequency stability of the beating oscillators, (ii) the tendency of the two oscillators to lock when their frequency difference was small, (iii) the loss introduced at low frequencies by the resistance-capacitance couplings between V_7, V_8, and V_9. Although these factors could be reduced to almost any desired extent by the use of adequate shielding, oscillatory circuits of low *L*/*C* ratio, and large coupling capacitances respectively, there remains one factor which sets a lower limit to the frequency that can usefully be employed. This factor is the limited persistence of vision, which requires that the picture-repetition frequency shall be at least 15 times per sec. At the lower end of the frequency scale, therefore, the steady-state response of the network under test is never reached, and the apparent shape of the response curve can be varied by changing the time-base frequency. For purposes of photographic recording, the repetition speed can be reduced and this effect eliminated, but, as the apparatus is designed primarily for visual indication, it has not been considered necessary up to the present to attempt to obtain frequencies much lower than 100 cycles per sec.

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* A. H. Reeves: "The Single Side-band System applied to Short-wave Telephone Links," *Journal I.E.E.*, 1933, vol. 73, p. 245

The tendency of the oscillators to synchronize at small frequency-separations gave rise to severe wave-form distortion at low frequencies, before actual locking set in. This was due to synchronization over part of a cycle and introduced harmonics in the input wave to the test apparatus, with a consequent error in the apparent low-frequency response. By the use of careful shielding and decoupling, this effect was reduced to a point where no tendency to lock could be detected, and the lowest beat-frequency obtainable was limited only by the frequency stability of the beating oscillators. The use of dynatron oscillators in place of the feed-back type was tried in an attempt to improve the frequency stability, but gave no improvement. Harmonics in the wave-form of the two beating oscillators were found to be more pronounced with dynatrons, and resulted in a number of beats between harmonics, instead of the single beat between the two fundamentals which is obtained from the two feed-back oscillators when the modulating valve V_7 is correctly biased.

(e) Rectification System

The conventional diode system of rectification is used, owing to its linear operation at large input voltages. The pentode V_9 will deliver an output of approximately 90 volts (peak) without distortion, which is sufficient for maximum deflection of a low-voltage cathode-ray oscillograph, so that no low-frequency or d.c. amplification is required after the diode. The values of the coupling condenser and leak between V_9 and V_{10} are somewhat critical, since too large a time-constant causes the response on the tube to lag behind the input to the terminals, 3, 4, with consequent distortion of the response curve. This effect is clearly shown by the faint image formed on the screen during the flyback periods of the time-base not coinciding with the much brighter image due to the slower forward motion. Reducing the time-constant reduces this effect, but introduces discrimination against the lower frequencies. Owing to the absence of any filtering system between the rectifier and cathode-ray tube, the response curve appears as a band instead of a line, the lower edge of the band being the zero line of the cathode-ray tube. This is an advantage, since it provides a base line from which the deflection can be measured.

(f) Crystal Frequency-Base

The chief feature of the crystal frequency-base, apart from those already described, is the use of the neutrodyne principle to overcome the effects of capacitance between the electrodes of the crystal-holder. The selective part of the 2-screen-grid valve amplifier forming the frequency base consists of two tuned circuits, coupled by two crystals in parallel. Owing to the relatively low decrement of these two circuits, very little coupling between them is necessary to produce an appreciable output from V_{12} at the frequency to which the circuits are resonant. A frequency separation of 12·5 kilocycles per sec., which is required to be " marked " on the oscillograph screen, represents so small a percentage change in frequency (less than 0·75 per cent) that, even in spite of their low decrements, small couplings produce a " blur " over the whole band. The crystals themselves behave as capacitances at all frequencies except those extremely close to their resonant frequencies, and in conjunction with the capacitance of the holder supply sufficient coupling to produce this " blur." By the use of a centre-tapped circuit and the neutralizing condenser NC (Fig. 1) any capacitance coupling is balanced out, and transmission through the amplifier can only take place when one or other of the crystals is resonant. By this means a satisfactory sharp line is obtained on the oscillograph screen at each crystal frequency. It will be observed that the position of these lines on the screen is dependent only on the controlled oscillator V_2, and not at all on the free oscillator V_4. The condenser C_2 of the oscillatory circuit of V_2 is made adjustable so that the marker lines may be brought into a convenient position on the oscillograph screen. Variation of the band-width control potentiometer R_1 alters the separation of the lines, but not, of course, the frequency interval which it represents.

(3) EXPERIMENTAL RESULTS

(a) Bias-Voltage/Frequency Relation

By applying various values of steady d.c. bias voltage to the grid of the control valve V_1, and measuring the frequency of oscillation of V_2 with an accurate absorption wavemeter, the curve shown in Fig. 4 was obtained. Since the horizontal deflection of the oscillograph spot is directly proportional to the bias voltage, it will be seen that a linear frequency-base is obtained over a range of more than 50 kilocycles per sec. Apart from possible synchronization effects at very low beat frequencies, this linearity will hold whatever the frequency of V_2, and consequent position of the band in the frequency spectrum.

(b) Amplitude Response of Pentode-Diode Combination

To test the linearity of the amplitude response of V_9 and V_{10} (Fig. 2), the time-base was disconnected and V_4 was set to give a constant voltage, at a suitable frequency at the terminals 1, 2, across which a potentiometer was connected, with the tapping point connected to terminal 3.

A suitably calibrated valve voltmeter was connected across the terminals 3, 4, and the length of the vertical line appearing on the oscillograph screen was used as a measure of the output voltage. The tube had previously been calibrated for deflection/voltage characteristics, so that from the two sets of readings the curve of Fig. 5 was obtained. Perfect linearity up to 90 volts (peak) output is indicated, and the rectification efficiency was found to be independent of frequency over the required range.

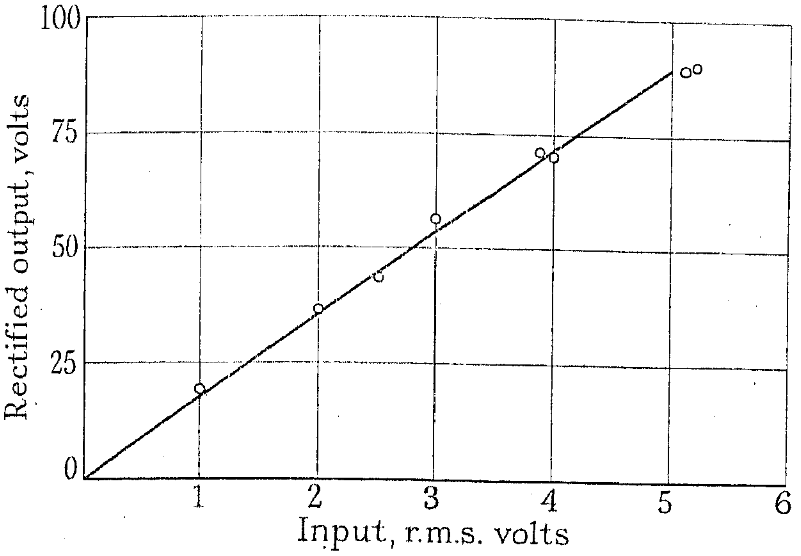

Fig. 5.—Amplitude response of rectifying system.

(c) Constancy of Output Voltage with Change of Frequency

The time-base was replaced in circuit, and the potentiometer arrangement described above was set to give a convenient deflection on the cathode-ray oscillograph. A series of "frequency sweeps" were taken at different positions of the band in the spectrum; these are shown in Fig. 6.

(4) APPLICATIONS

(a) Measurement of Response Curve of an Intermediate-frequency Transformer

Fig. 7 shows the frequency response curve of a certain commercial type of intermediate-frequency transformer when working in conjunction with a high-frequency pentode valve. The curve shown was traced from the screen of the cathode-ray tube, the positions of the marker crystals being shown by vertical lines. The two lines to the right are due to the same crystal, which had a number of crevasses close together, and careful adjustment of the bias voltage on V_{11} and V_{12} was necessary to eliminate all but two of these.

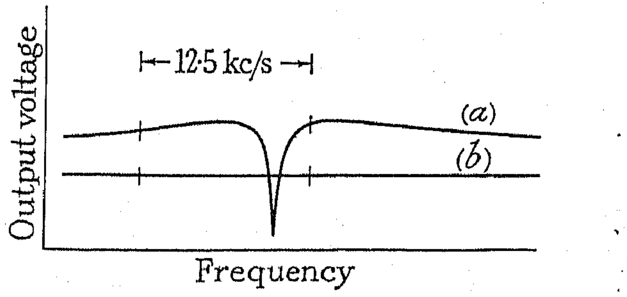

Fig. 6.—Output/frequency curves.

Curve (*a*): Mid-frequency = 0.
Curve (*b*): Mid-frequency = 98 kc.

The vertical scale shown below the response curve is a linear frequency-scale, and is a final check on the linearity of the horizontal frequency-base. The oblique lines join points on the oscillograph screen at which the cathode-ray spot was brought to rest (by a steady bias on the grid of V_1 instead of the time-base), with the actual output frequency corresponding to this bias, as measured by an absorption wavemeter. The degree of parallelism between these lines is thus a measure of the linearity of the frequency/grid-bias relation—similar to that discussed in Section (3)(*a*) but now at the actual operating frequency, instead of at one of the beating frequencies.

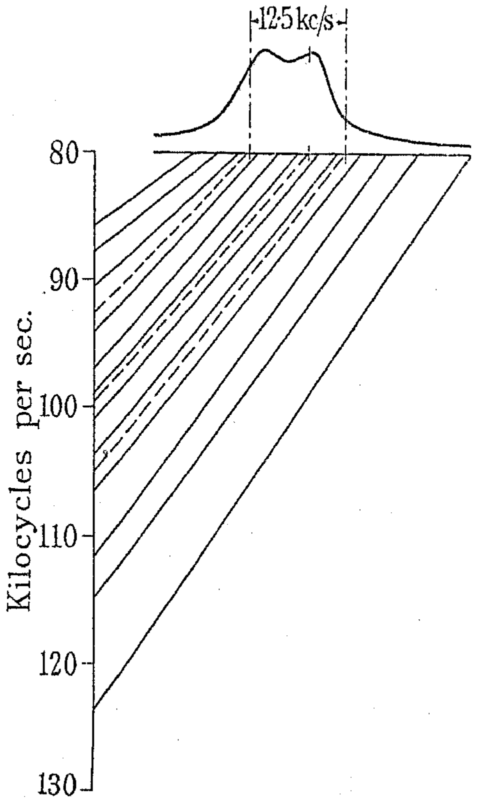

Fig. 7.—Response curve of an intermediate-frequency amplifier.

The lack of exact linearity was found on examination to be more apparent than real, the frequency-change per cm of deflection varying in a random manner, owing to experimental difficulties in locating the stationary spot exactly in the presence of halation effects. The perfectly linear nature of the curve of Fig. 4 is a reassurance on this point. Fig. 8 shows a photograph of the response curve of the same transformer.

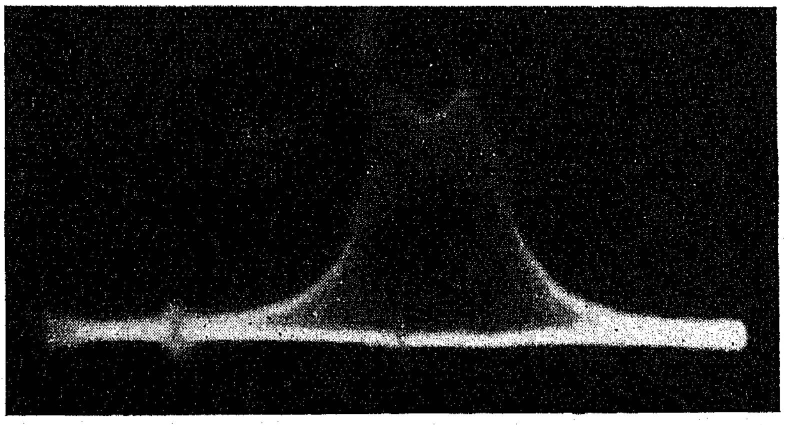

Fig. 8

(b) Further Applications

The measurement of the overall response of a broadcast receiver is an obvious application of the instrument, but a second stage of heterodyning would be necessary in order to bring the mid-band-frequency up to the region of 1 000 kilocycles per sec. For example, the apparatus might be set to produce a band extending from 390 to 410 kilocycles, which would then be heterodyned with a 600-kilocycle oscillator, thereby producing an upper side-band extending from 990 to 1 010 kilocycles. In the case of a receiver with automatic volume control, it would be necessary to maintain a steady carrier, so that the apparatus would be used to modulate a 1 000-kilocycle oscillator at a frequency varying from 0 to 20 kilocycles.

The measurement of the response curve of a loud-speaker is another application. The loud-speaker is connected to the terminals 1, 2, and a microphone of known characteristics is connected to terminals 3, 4. Such an application has previously been described in connection with the mechanically-operated systems mentioned at the beginning of the paper.

A rather different use for the instrument lies in the field of analysis of complex wave-forms, in a manner analogous to that used in the "sound prism."* The wave-form to be analysed would be heterodyned with a steady oscillator so as to bring one of the side-bands to approximately 200 kilocycles per sec. This band would then be applied, together with the sweeping frequency, to a detector valve and low-pass filter connected to the terminals 3, 4. The resultant pattern on the oscillograph screen would then indicate the relative amplitudes and frequency-separation of the components in the original wave-form.

The operation of the apparatus as a wave analyser can be readily shown by inserting a sharply resonant circuit between the terminals 1, 2, and 3, 4; and adjusting the bias on V_5 so as to produce a badly distorted wave-form on the control grid of V_6, when a series of resonance curves can be obtained on the screen, each one corresponding to a harmonic in the wave-form. This effect is a useful check on the correct operating conditions of the various valves.

ACKNOWLEDGMENT

The development of the apparatus described in this paper was carried out in the post-graduate Communications Laboratories of the City and Guilds College, with the assistance of various post-graduate students, including, at different times, Mr. J. Grensted and Mr. T. Worswick.

The author wishes to thank Prof. C. L. Fortescue for the interest he has taken in the work and the suggestions he has put forward regarding the problems involved.

DISCUSSION BEFORE THE WIRELESS SECTION, 1ST APRIL, 1936, ON TWO PAPERS BY PROF. FORTESCUE† AND A PAPER BY MR. REID‡

Lieut.-Col. K. Edgcumbe: I shall confine my remarks to the paper on hot-wire ammeters by Prof. Fortescue.

In the first place, I presume that the author is convinced that a hot-wire instrument is to be preferred to a thermocouple instrument. The latter fulfils the requirement of being based on the heating of the conductor, and I should have thought that it was easier to deal with, both theoretically and practically, than an instrument which has so many component parts; on the other hand, the capacitance will be less easy to calculate.

I should like to thank the author for emphasizing the fact that increasing the scale length does not increase the accuracy. Actually I think that the accuracy goes down, because nearly all the intrinsic errors of the instrument go up. If the error of the instrument itself is 5 per cent there is not much use in reading its scale to 0·1 per cent.

The author says that it is the simplest thing in the world to ensure that the current divides itself evenly between the wires in his ammeter. My experience, however, is that at these frequencies one does not know where the current will go. The author simply says: "If the length and diameter of the wires are all the same, the inductance will be the same, and this alone is sufficient to ensure that the high-frequency current will be equally divided between the wires." I hope that this is so, and in any case I take his word for it.

Lastly, I should like to ask what method he uses for testing these instruments. I saw a proposal the other day which rather interested me; it consisted in mounting a straight filament in a vacuum and sending through it a current sufficient to make the filament thoroughly incandescent. The value of the current was then determined in terms of the output of a photoelectric cell placed nearby. The advantage of the method is that it makes possible the use of a comparatively small wire for a heavy current, and should therefore make a useful transfer instrument for comparing direct currents or low-frequency currents with radio-frequency currents. This device would not make a satisfactory ammeter, since the scale would be a very short one, the luminous output being proportional to the fifth power of the current; but that is an advantage in another respect, because it means a very sensitive ammeter so long as only the upper part of the scale is used.

Mr. E. C. S. Megaw: I propose to confine my remarks to the two papers by Prof. Fortescue.

I have lately attempted to make accurate measurements of voltage at frequencies ranging between 30 and some hundreds of megacycles. As a result of my work in this direction, I must say that I do not quite share the author's pessimism with regard to the possibility of evolving a reliable peak voltmeter. The general analytical results I have obtained, so far as one can analyse these rather complicated problems at all, are in complete agreement with those which the author puts forward.

The question arises of how far we can hope to reduce the errors due to the approach to resonance in the voltmeter circuit and to the transit time of the electrons; and, if they cannot be reduced to dimensions consistent with accuracy, how accurately can we calculate the corrections for them?

Taking first the question of approach to resonance in the voltmeter circuit, we have found that, using diodes substantially the same in design as the one described in the paper, the difficulty introduced by this factor is not very serious, even for frequencies up to about 100 megacycles, provided that we have to measure only the voltage between two adjacent points, one of which is earthed. Our experimental evidence seems to show that in those circumstances errors not greatly exceeding 1 per cent are obtained. If, however, it is necessary to measure the voltage between two points which are, say, 1 yard apart, at a frequency of 50 or 100 megacycles, even if one of the points is earthed the problem is a good deal more difficult, and we have found that the best way to measure the voltage is to provide an artificial earth point close to the unearthed terminal. At wavelengths of about 1 metre this can be done by hanging up a few pieces of wire $\frac{1}{4}$ wavelength long, and connecting one end of each wire to the cathode of the valve. Quarter-wavelength wires, their other ends hanging freely, provide a circuit which has a low impedance with respect to the surrounding bodies. Such a device enables one to make measurements at wavelengths down to 0·5 metre, not perhaps with accuracy but with some fair approach to what we believe to be the true voltage.

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* O. H. SHUCK: *Proceedings of the Institute of Radio Engineers*, 1934, vol. 22, p. 1295.

† "Thermionic Peak Voltmeters for Use at Very High Frequencies" (see vol. 77, p. 429) and "The Theory and Design of Hot-Wire Ammeters for Frequencies of 25 to 100 Megacycles" (see page 179).

‡ See page 194.

At wavelengths less than about 0·5 metre it is almost impossible to make a voltmeter circuit so small that the reasonance error is negligible, and the arrangement which we have adopted in these cases is to connect the voltmeter to the terminals at which we are trying to measure the voltage through a pair of conductors which form a transmission line whose electrical length is half a wavelength, or perhaps an integral number of half-wavelengths. If we do this, and provided the damping of the line is not too big, then the voltage produced at the actual measuring terminals is substantially the same as that at the terminals where the voltage is to be measured 1 electrical half-wavelength away. The difficulty, however, is to know when one has actually got an electrical half-wavelength—a separate determination to the "equivalent length" of the voltmeter input impedance must be made—but it is at least a method of getting over what otherwise seems to present some difficulty.

Considering now the transit-time error, here also the difficulties are rather great. The calculation seems to be practicable only for the simplest case of a uniform electric field, or in other words a parallel pair of electrodes with no space charge. The following method suggested itself as a way of checking experimentally whether the results calculated from such a simple formula did agree with what might actually be observed. The method was very simple; it consisted of maintaining a constant voltage at a certain point and obtaining with a voltmeter a series of readings with a number of diodes having identical physical properties but different inter-electrode spacings. It was to be expected that the error, at any rate when not too large, would be proportional to that spacing, and the results indicated such a linearity. By extrapolating those results, we were able to see what the result would have been in the absence of any transit-time effect. To sum up, it seems that the error is about twice as big as we had expected it to be from the simple theory.

A commercial diode of this type has now been developed with which it appears to be possible to make measurements of voltages greater than perhaps a few tens at frequencies up to 100 megacycles with errors not exceeding about 10 per cent.

Turning to Prof. Fortescue's paper on the hot-wire ammeter, I also feel that from the user's point of view it would be interesting to know why the author chose to make this very useful and very thorough examination of the mechanical method of noting the change in temperature of the wire rather than the electrical one; i.e. why he investigated the hot-wire ammeter rather than the thermocouple type. It seems to me that the thermocouple ammeter has two definite advantages: first of all, in this ammeter it is possible to separate the indicating part from the high-frequency part, and secondly the size of the high-frequency part can be made a good deal smaller. The precise calculation of the errors is perhaps more difficult with existing forms of thermocouples, but I should be interested to know whether the author considers that one might so design a thermocouple arrangement that its errors could be accurately calculated. Can he tell us what is the accuracy of commercial thermocouples relative to his hot-wire instrument?

Mr. B. W. S. Challans: I propose to confine my remarks to the paper by Mr. Reid.

I have used the Miller effect in the valve which was mentioned by him, and I find that if one keeps the anode resistance low the resistive feed-back is also low, using bonded carbon resistances. This arrangement has the advantage that, in order to get a linear frequency/output characteristic, it is merely necessary to obtain a square-law valve. Many valves are reputed to be of the square-law type, but I have had a good deal of difficulty in finding one which actually is so, i.e. one which has a straight-line mutual-conductance/grid-volts curve.

The author used a response curve consisting of a band instead of a line, and he claims that this has the advantage of giving a reference line at the bottom of the curve. This reference line is of doubtful use, because generally—commercially, at any rate—one is interested merely in the centre portion of the curve, and the reference line is obtained at the expense of brilliance.

With regard to the suggestion that this is the first form of response-curve analyser or response-curve projection apparatus not using rotating condensers, I have in my laboratory at present an American ganging oscillator which uses some form of Miller effect and gives three fixed output frequencies with a frequency variation of ±15 kc on either side.

In connection with the low-frequency end of his frequency output the author mentions the use of a low-frequency sweep. It does not seem to be generally realized that it is most important to use a low frequency always, because if one is examining circuits of low decrement the phenomenon which is sometimes known as "ringing" will come in. Also, some two years ago Barrow* showed that what is actually obtained is a spectrum consisting of discrete frequencies displaced by the actual frequency of the frequency modulation.

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* *Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 1182.

If the rate of sweep is too high, a decreasing number of discrete frequencies will be contained in the band which is being considered, the number becoming more limited as the rate of sweep is increased. In the limit, the fundamental frequency only will be received, the adjacent frequencies being outside the band under consideration, and a false resonance curve will be obtained.

Dr. E. H. Rayner: In measuring radio-frequency currents one naturally follows out to a considerable extent the ideas that one uses for power-frequency currents. One of these is that when dealing with precision measurements of alternating currents it is necessary to reduce the errors as far as practicable by raising the specific loading of the conductors which are being used. We have a resistor at the N.P.L. composed of many miles of wire, and the rated loading of the wire involves a temperature-rise of 100 deg. C. under normal conditions. This becomes necessary in order to reduce the time-constant to as small a value as possible. In radio-frequency measurements we are dealing with frequencies of the order of 1 million times as great, and the troubles are very much enhanced: one therefore looks to this factor of high specific loading as a way out of the troubles of radio-frequency current measurement. In other words, let us run the resistor, of whatever material it may be—in Prof. Fortescue's instrument it is of platinum-alloy wire—to the highest temperature we possibly can. This idea is in line with the suggestion which Col. Edgcumbe mentioned of using a wire white-hot. We have recently been doing some preliminary experiments on the use of incandescent wires as indicators of temperature and incidentally of the value of the current, and they are not unpromising. We have not yet attempted to use radio-frequency currents; but using direct current we find that we can reproduce a reading to the order of 1 part in 1 000 by means of measuring the illumination output with a suitable photocell. As Col. Edgcumbe mentioned, one is limited in the range of each particular resistor, but as the range is of the order of 2 to 1 there is no great difficulty; and there is also the advantage that, although the range for each particular resistor is small, the sensitivity is correspondingly high on account of the very rapid rise of luminescence with current and temperature. The method has been used in other countries.

Experience of hot-wire instruments in past years shows that there is always liable to be an indefiniteness in measurements depending upon the increase of resistance of a wire cooled by the surrounding air; and the more definite effect of luminous radiation promises to be more precise as a basis for a standard method. This does not imply that the apparatus devised by Prof. Fortescue is not capable of filling quite an important place; but it seems not impossible that as a result of the recent rapid developments in the design and use of photocells a satisfactory switchboard type of photo-operated instrument may be developed.

Mr. L. A. Moxon: I propose to confine my remarks to Prof. Fortescue's paper on the hot-wire ammeter.

I am particularly interested to notice that an instrument has been constructed using an inductive shunt. It seems to me that this arrangement offers the advantages of lower cost, simpler construction, greater reliability, reduced terminal capacitance, lower power factor, the possibility of constructing multi-range instruments, and, in particular, very considerable reduction in the impedance, especially as regards instruments for measuring large currents. If one takes, for example, an instrument for measuring a current of 6 amperes, and considers the earlier type of multi-wire construction, the largest number of wires which can conveniently be used is probably of the order of 6. If we compare a single 0·25-ampere wire shunted by an inductive shunt with an instrument consisting of six 1-ampere wires in parallel, we find that the impedance is reduced in the ratio 4 : 1. Further advantages of the inductive-shunt arrangement are the reduction of the capacitance of the instrument to earth, and of the total mass of metal that is essential to the instrument. In this connection it may even be worth while going to the length of making the case of the instrument, and also as much as possible of the mechanical system, of insulating material. It seems to me that, unless these precautions are taken, when the meter is inserted into any high-frequency system that system is going to be upset thereby unless one is able either to take precautions with regard to balancing out the earth capacitance of the instrument or else to insert the instrument in the system so that the earth terminal is at a nodal point. In practice that may be a very difficult thing to do.

It is understood that the calibration of a hot-wire ammeter employing an inductive shunt is difficult to calculate, and it must probably be obtained by comparison with an instrument of the earlier type.

Mr. A. J. Gill: In the early days of the use of hot-wire instruments we generally found that the needle was well off the zero when we started to measure. Having adjusted it to zero, obtained a reading, switched off, and allowed the instrument to cool, we quite commonly found that the pointer was still off the zero. I presume that these difficulties have now been overcome.

In looking at the curves in Prof. Fortescue's paper on the hot-wire ammeter I am impressed by the wonderful coincidence between the readings of instruments Nos. 3 and 5 at a frequency of 40 megacycles; I do not know of any other current- or voltage-measuring device operated at frequencies above 10 000 cycles with which one can obtain such coincidence in measurements.

There are one or two small points about which I am not clear. Fig. 7 of the same paper shows four wires, and two of the ends are marked "H.T. terminals." It is not quite clear to me what is the path of the currents, i.e. whether they go down the tube and get back to the screen case, and whether the wires in the top tube and the bottom tube also carry currents or not. Again, referring to Fig. 6, I take it that the current passes down the central wires and goes to the screen, so that the screening tubes are at the mean potential and no current goes down the multiplying wires; but are any steps taken to exclude the current from the multiplying wires? Presumably there will be some little impedance in that strip at the end of the tube which will act as a shunt and tend to divert some of the current down there. Presumably these are not very important points, because the instrument works quite satisfactorily.

In the paper on the peak voltmeter, Prof. Fortescue refers to the possible difficulty of resonance. I should like to suggest that such a possibility is very remote.

The paper by Mr. Reid is very interesting to me because we in the Post Office have done some work of the same character, using a rotary condenser. With any device of this kind it is necessary to use the slowest possible traverse, or a spectrum will be obtained consisting of spot frequencies rather than a continuous change. There is not very much advantage in using an electrical method of frequency modulation as compared with the method employing a rotary condenser, because the rate of traverse need be only 25 cycles per sec. or less, and it is very easy to make a condenser with two or four blades in it to give that variation. We have used one of that type, but for some time past we have been experimenting with the electrical traverse. We do not claim any priority in this direction; it is simply that we seem to have struck the same idea as the author.

Mr. K. I. Jones: I propose to confine my remarks to Mr. Reid's paper, and to deal with the subject from the point of view of the use of the apparatus for the design of broadcast receivers.

It seems to me that this apparatus is more useful for the inspection of the characteristics of a complete amplifier than of an individual filter, inasmuch as one can calculate the response of a filter with a certain amount of ease, and one can also measure it, but in a complete receiver there may be stray feed-back in the wiring and feed-back due to grid-anode capacitances in the valve which can make the actual resonance curve quite different from that calculated. Moreover, the accuracy obtainable by plotting the response curve on a cathode-ray oscillograph is not as good as can be obtained by other methods, particularly as the output is linear and not logarithmic; for selectivity curves the latter is often desirable. The great advantage of the apparatus, however, seems to me to be that one sees the whole response curve at once, instead of merely the voltage at one point on that response curve.

In view of the fact that one wishes to use the apparatus to examine a complete receiver or amplifier, it is necessary that the detector circuits should not be changed. If such changes are made the stray capacitances are altered on going over to the reception of wireless signals, and of course the ganging is affected. This difficulty can be overcome by using the detector in the receiver itself to rectify the frequency-modulated input. It is usually then necessary to amplify the output of this detector; otherwise it is possible that valves in the chain previous to the detector may be overloaded.

It seems to me that when the apparatus is worked on frequencies round about 100 kc, which are quite usual, the stability of calibration will not be very large. For instance, an accuracy of 1·7 per cent at 100 kc demands a stability on the part of the oscillators themselves of 0·1 per cent, which they would probably hold, I suppose, over a period of hours, but hardly over a period of months.

I agree heartily with the author that the electronic method of frequency traverse is much more flexible and more desirable than the mechanical method, and from the radio designer's point of view, apart from the speed and accuracy with which it enables receivers to be aligned in production, it is extraordinarily useful in finding out just what experimental receivers are doing. A point in this connection is that where Miller effect due to the grid-anode capacitance of the valve is present, if one tunes the oscillatory circuit in the anode of that valve the feed-back becomes a negative resistance in parallel with the input circuit, and, although the circuit in the anode is off resonance, the gain is considerably enhanced, so that by ganging such a set with an output meter the anode circuit is misganged.

Mr. J. E. Marshall: I wish to refer to Mr. Reid's paper and to mention one rather interesting method of controlling the oscillator frequency which does not seem to have been touched upon, and that is a scheme which is used for automatic tuning. I am referring to the use of the reactive control valve. In this method, the grid of the valve is fed from the anode through a phase-changing network which brings about a phase-change of 90°, i.e. the valve is made to appear as an inductance. The value of this inductance can be varied by varying the grid bias to the valve. The method suffers from the disadvantage of variable damping of the tuned circuit to which it is applied, but it seems to me that this difficulty could be very easily overcome by applying A.V.C. to the oscillator so that its output is maintained constant. There is another possible method of achieving constant output, depending on the use of an anode-bend rectifier: one heterodyning signal is made very much stronger than the other, in which case the required heterodyne output is proportional to the weaker signal, the frequency of the stronger signal being the variable.

It occurred to me in watching the author's demonstration that the very low sweep frequency used was rather trying. In carrying out experiments on this particular scheme I have used a frequency of 25 cycles with complete success, the time-constants giving no trouble if carefully arranged. There is also the possibility of using instead of the thyratron time base the 50-cycle mains as the variable grid bias for the control valve and also for the horizontal sweep of the oscillograph.

Mr. W. L. McPherson: Prof. Fortescue, in his paper on peak voltmeters for use at very high frequencies, mentions that the frequency error depends on the assumptions that the electrode capacitance is a definite constant and that the distributed capacitance of the leads can be neglected. At the very high frequencies such as are used in micro-rays it is impossible to neglect the distributed constants; it is far easier to assume that everything has distributed inductance and capacitance. Under these conditions it becomes very difficult to apply any ordinary type of instrument, and the type of ammeter which Prof. Fortescue has designed would, I think, be inapplicable simply on account of its size; it would occupy an appreciable proportion of a wavelength in which definite current changes might occur. On the micro-ray equipments with which I have been concerned the only consistent measurement which we have been able to make is that of power, which has been measured by a thermocouple system connected through a tubular-type transmission line so that one side of the system is always earthed. A fairly definite measurement of power can also be obtained by terminating the line in a very short filament and measuring the luminosity by any photometric method, comparing it with the luminosity from the same filament when fed with direct current. As the length of the filament is only $\frac{1}{8}$ in., the standing-wave question does not arise. Measurements of peak voltage have been made across relatively low impedances of the order of 70 to 100 ohms. I should not like to guarantee the accuracy of these measurements to anything greater than 10 per cent, and this figure is probably optimistic, but it is of interest that the power can be measured to within even that accuracy at frequencies of, say, 1 500 megacycles.

Mr. Charles Holt Smith: I have been very interested in Mr. Reid's paper and demonstration, as I have been developing apparatus on somewhat similar lines myself. I have, however, adopted a completely mechanical drive. It is interesting to compare the manner in which Mr. Reid's apparatus and my own have, by dissimilar means, arrived at the same ends. The advantage which I have found from adopting a mechanical drive is that it enables one to deal in static terms with the response curve; that is to say, one can examine minutely and for an indefinite period the precise shape of the response curve at any specific point. Another advantage is the fact that we have been able quite simply, by means of cams, to draw a baseline during the fly-back period without the necessity of tracing out an area, and we have thereby had the dual advantage of a zero baseline and a brilliant trace.

I am rather surprised that Mr. Reid's paper does not pay more attention to the effects of the frequency at which the picture is traced on the actual shape of the picture. I found quite a definite indication of the fact that the shape of my picture was dependent on the picture frequency, and the effect was demonstrated quite simply, using the mechanical system, by reversing the direction of travel of the motor and reversing thereby the departures from the true picture which occurred due to the finite picture speed. When dealing with filters having a very short cut-off, the maximum speed which should be used was of the order of a very few cycles per second to avoid any distortion of the true picture, a speed so slow that the blue or green tube gave very unpleasant flicker effects, and I therefore had to use a strontium tube with its very good afterglow. The problem was very much simplified thereby.

THE AUTHORS' REPLIES TO THE DISCUSSION

Prof. C. L. Fortescue (*in reply*):

The High-Frequency Ammeter.

Several speakers have mentioned the intrinsic disadvantages of the hot-wire system—indefiniteness of zero in particular. For low-frequency precision work these criticisms are justified, especially in the hot-wire voltmeters where the consumption of energy is considerable. In some very cheap forms of hot-wire ammeters the criticism is also perhaps apposite. But in the case of ammeters in which hot wires of relatively low resistance are carrying currents of from 0·25 to 1·0 ampere, in which the temperature-rise above the surroundings is fairly high, and in which the mechanical magnification is not too great, the zero-keeping is reasonably good. Inaccuracy arising from this cause is not serious at frequencies above 25 megacycles, since other errors are much greater.

The relative advantages of the thermocouple and the mechanical magnification have also been mentioned by several speakers. The thermocouple was ruled out in the present case owing to the uncertainty with regard to the possibility of skin effects of incalculable magnitude and of induced currents in the junction and the leads to it, which in themselves might cause more heating of the junction at high frequencies than that due to the current actually being measured. Where the instrument can be calibrated against a standard over the whole range of frequency, the thermocouple is unquestionably the more convenient. But where a low-frequency calibration has to be used, since there is no high-frequency standard available, the symmetrical co-axial wire and cylinder with some means, which is unaffected at high frequency, of observing the temperature is essential. The actual means employed for measurement of the temperature does not change the principle. Very hot wires with photometric methods of comparison are certainly a possibility, provided that errors are not introduced by either incomplete screening or by variation of the skin effect due to the variation of temperature along the heated wire. But the photometrical method is far more complicated and, since the errors of the mechanical magnification are less than other errors not yet overcome, it seems unnecessary to adopt this method. The one possible advantage is that stressed by Dr. Rayner, viz. that the impedance may be less in instruments employing high temperatures. As to whether this advantage can actually be realized has yet to be established.

Mr. Moxon is in favour of the instrument having an inductive shunt. As a practical instrument it has advantages, but it must be calibrated against a standard at all frequencies and is thus no real advance on a thermocouple instrument, except possibly in the matter of its low impedance.

In reply to Mr. McPherson, no attempt has yet been made to obtain accuracy at frequencies approaching 2 000 megacycles.

The Peak Voltmeter.

Mr. Megaw's experiences are very interesting and, in spite of Mr. Gill's remark to the contrary, there is no question but that resonance is a most serious difficulty. Mr. Megaw's suggestion of an artificial earth is ingenious, but it is to be feared that it does not wholly circumvent the difficulty. There is some evidence that the error due to time of flight as calculated in the paper is an overestimate, but the experimental measurement on which alone a conclusion can be based is very difficult.

Mr. D. G. Reid (*in reply*): Mr. Challans mentions the use of the Miller effect as an alternative means of producing the frequency variation. On theoretical grounds there would appear to be very little difference between the two methods, both depending as they do on the curvature of the valve characteristics. As Mr. Challans points out, it is necessary when using the Miller effect to employ a valve having strictly parabolic characteristics, and such a valve, as he admits, is not always easy to find. Replacement of one valve by another may then cause a substantial change in the shape of the frequency-control voltage characteristic. With the frequency-control principle which is used in this apparatus, the ideal shape of characteristic required by theory closely resembles that of an ordinary low-impedance output triode, and reference to Fig. 4 of my paper will show how closely linearity of frequency with grid-bias voltage is maintained over the requisite range of frequencies. It was found in working with the apparatus that it is not at all critical of the type of control valve used, and many different types of low-power output triodes were used at different stages in its development.

It may be pointed out that the use of the Miller effect in no way avoids the difficulty of varying load on the oscillatory circuit and the amplitude changes which it produces, since the input admittance of a triode having grid-to-anode capacitance is a complex one, having an in-phase conductance component which varies with the grid bias in the same manner as does the leading susceptance component.

The use of a band of light instead of a line diagram unavoidably reduces the picture brilliancy, but, nevertheless, the picture obtained is still sufficiently bright for photography or examination in daylight. It was felt that the advantages of having a base line available, together with the avoidance of errors in wave-form due to a large time-constant in the rectifier circuit, outweighed the disadvantage of low brilliance. As Mr. Challans points out, in all forms of frequency response curve apparatus what is really examined at any instant is the response not to a steady sinusoidal wave of constant frequency but to a frequency-modulated wave, and it is only when the modulation frequency is extremely low compared with the "fundamental" or carrier frequency that the resulting spectrum of infinitesimal voltages of continuous frequencies may properly be considered as degenerating into a single-frequency voltage of finite amplitude.

I am interested to hear from Mr. Gill that the Post Office have been working along the same lines, and are now experimenting with electrical frequency-sweeping in place of the rotating condenser. It would appear to me that the use of motor-driven condensers is to be avoided wherever possible in any apparatus in which portability is aimed at. He may be interested to know that, since the paper was written, the same principle has been applied to a "warbler oscillator" operating at audio frequencies, which appears to have possibilities as to standard source of noise in interference measurements.

Mr. Jones comments on the application of the instrument to the measurement of the overall response of an amplifier or radio receiver. It is of course essentially suitable for this purpose, and the demonstration in connection with a single intermediate-frequency amplifier was purely to show the type of picture obtained.

The stability of the two beating oscillators is an important point, as it determines the practicable lower limit of frequency at which the apparatus can be operated. For taking the response curves of low-frequency amplifiers, lower beating frequencies would be advantageous.

Mr. Marshall makes an interesting suggestion regarding the use of a reactive control valve. Essentially this is very similar to the Miller effect, except that by the use of a suitable phase-changing network the grid-input admittance can be made more nearly a pure reactance than is the case when the grid-anode capacitance alone is relied upon, as in the Miller effect. The use of automatic volume control to avoid the effects of variable damping was considered, but the equalizing circuits used correct the amplitude variation almost completely and have the advantage of simplicity.

The principle of rendering the beat output independent of one of the heterodyne voltages by making one very much larger than the other was tried at an early stage in the development of the apparatus, but it was found that the large voltage-swings which it is necessary to apply to the grid of the modulator produce large numbers of high-order harmonics, resulting in a number of response curves appearing on the screen at once.

The use of the 50-cycle mains as a low-frequency source was also tried, but here again the resulting two pictures for the two half-cycles produce a blurred image owing to inevitable slight phase-changes. Furthermore, with a sinusoidal low-frequency sweeping voltage the illumination of the picture is greater at the sides than in the middle, where greatest detail is required.

Mr. Smith puts forward as an advantage of the mechanical system the fact that portions of the curve can be examined statically by turning the condenser by hand. The same can be done with electrical sweeping, by substituting a battery and potentiometer for the time base. The curve of Fig. 4 was obtained in this way. His suggestion for using tubes with long afterglow should prove valuable in dealing with low-frequency amplifiers where the sweeping frequency must be kept very low.

ELECTRICAL INTERFERENCE WITH BROADCASTING

(Report of a Committee, unanimously approved by the Council, 2nd July, 1936.)

Preface

The Council will recall that in 1933 they appointed a small "preparatory Committee" to review the subject of interference with radio reception. This preparatory Committee reported in April, 1933, and advised the Council that serious interference appeared to be taking place, reviewed the extent of this, and indicated the measure of technical advance towards ascertaining the best methods of curing the trouble.

As a result of that report the Council appointed the present representative Committee with the following terms of reference:

(*a*) To consider the report (drawn up by the preparatory Committee appointed by the Council) setting out the problems to be solved.

(*b*) To make recommendations as to the steps, if any, to be taken to secure the elimination or mitigation of electrical interference with radio reception.

(*c*) In connection with (*b*) above, the Committee are requested to consider, *inter alia*, the following specific matters:—

  (i) The degree of immunity of each type of apparatus, and the degree of interference from each type of electrical plant and the best means for its elimination.

  (ii) The desirability of embodying in specifications for new plant the requirements for interference suppression.

  (iii) The desirability or otherwise of legislation.

We submitted to the Council an interim report on the 18th October, 1934, indicating the various phases of the subject which we were studying, and the progress being made.

We now have the honour to submit our final report on the subject. From this we hope the Council will see that their Committee has not merely been studying the subject, but has stimulated action by various bodies with a view to clarifying such questions as standards and measurement of interference. We have also endeavoured, as far as we legitimately could as a Committee, to encourage the application of radio-interference suppression devices. This side of our activities has been the easier because the Council had appointed to their Committee representatives of all organizations which were likely to be interested or to be able to help in securing general collaboration in the electrical industry. In Appendix I we give a list of these organizations and their representatives on the Committee.

Altogether 95 meetings of committees dealing with radio interference have been held in the 3 years which have elapsed since the Institution Committee was set up, as follows:—

Main I.E.E. Committee and Sub-Committees ..	62
B.S.I. Committee and Panels	20
E.R.A. Committee	13

1. Previous Report.

When we presented our first report to the Council (in October, 1934), although we were able to recommend an objective limit we were unable to say that the technical position was sufficiently advanced to justify the drawing up of formal regulations for the suppression of interference. This was mainly because none of the methods proposed for assessing and measuring interference was sufficiently established to give us confidence in its suitability for practical application.

2. Objective Limit.

The recommendation in the above-mentioned Report still holds good as to the objective limit which is desirable; that is to say, there should be a difference of at least 40 decibels between the strength of the signal (or wanted) field* and the interfering (or unwanted) field. But the step has been a long one between defining the objective we should like to reach, and finding a yardstick—or perhaps more than one—which can be applied practically to the several very diverse groups of conditions which give rise to radio interference.

3. Method of Measurement.

A method of measurement has now been agreed upon and instruments have been developed which are capable of indicating with sufficient accuracy the amount of interference caused by much of the electrical apparatus which causes trouble.

4. Technical Position.

Technically, therefore, the position is that a method of determining interference caused by many types of apparatus is now available, and in the majority of these cases it is not considered that any undue extra expense will be involved in the design and construction of such apparatus to bring the interference caused down to an acceptable standard.

5. Apparatus to be corrected.

The apparatus which is likely to cause the most interference is comprised in the following groups. Most of the trouble from radio interference would be eliminated if these could be satisfactorily dealt with:—

1. Lifts in buildings.
2. Trolley-buses and trams.
3. Household electrical appliances.
4. Small electric motors used in commercial premises.

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* Of the order of 1 mV/m, modulated 80 %.

(5) Neon display signs.
(6) Certain rectifiers for power plant.
(7) Electro-medical apparatus.

A brief account of the studies undertaken and the progress made in connection with the above groups is given in an Appendix to this Report (Appendix II).

6. Ignition Systems and Television.

In addition to the items listed in paragraph 5, the ignition systems on automobiles must be mentioned, although at present there is no appreciable interference from automobile ignition with ordinary broadcast reception on its present wavelengths. If, however, such systems continue in use uncorrected it is probable that there will be interference with television reception. How troublesome this may be will only be known when the television service begins.

7. Other Sources of Interference.

There are other groups of apparatus which might be, and occasionally are, the cause of radio interference, for instance, electric signalling gear on railways. So far as these groups are the cause of trouble they will doubtless be corrected in due course, but they are not at the present time to be reckoned amongst the major causes of radio interference.

8. Progress achieved.

The progress towards precise definition of the best way of measuring the interference caused by apparatus in each of the above groups, and the most effective method of correction, is greater in some than in others, but with all of them we can say that, technically, radio-interference correction is possible, although, from the point of view of cost, some cases are relatively more expensive to rectify than others. In all groups a considerable measure of radio-interference correction has been taking place during the last few years, as a result of Post Office activity combined with voluntary application of the indicated remedies. But this has only been effected in individual cases and as the result of listeners' complaints.

9. Traffic Signals.

The first case in which radio-interference correction was in effect made compulsory was that of traffic signals. The Ministry of Transport require all traffic signals to be supplied to British Standard Specification No. 505—1933. The fitting of correcting components was, from the first, one of the requirements of this B.S. Specification, and the result has thus been achieved without serious difficulty.

10. Trolley-buses.

A second case in which much practical progress has been made is that of trolley-buses, where again the Ministry of Transport have influence in securing attention to the matter on the part of those who are in a position to help, and who have in fact co-operated willingly with the Ministry to this end.

11. Compulsory Powers versus Voluntary Action.

As it became clear to us that the various technical aspects of the problem were approaching solution, we felt we ought to give renewed consideration to the important question whether compulsory powers should be conferred on some Authority to require radio-interference suppression in cases in which it appears that this will not be achieved effectively without the application of such powers. It became evident from the discussions of the Committee that the majority of members did not consider that effective interference suppression would result if the improvement of the position were to be left solely to voluntary effort. The manufacturers of appliances and plant which are liable to cause interference definitely support this view, and they consider that there should be some recognized Mark which could be affixed to all portable appliances as a guarantee that such appliances comply with the requirements, and that the sale of appliances which do not meet with these requirements should be prohibited. Further, it is essential that imported articles should be subject to the same regulations as home-produced articles and should bear the Mark, and it is only through legislation that this question can be dealt with successfully. Frequently it is not the man who buys and uses the apparatus, but his neighbour, who suffers from the resulting interference. For these reasons, and also because of the difficulty of dealing with imported apparatus, the British Electrical and Allied Manufacturers' Association is in favour of some form of compulsion.

12. Form of Compulsory Powers in connection with New Apparatus.

It appeared to the majority of the Committee that the problem was one which could best be solved satisfactorily by giving powers to some Authority, acting under suitable technical guidance and safeguards, to issue, from time to time, regulations appropriate to the design, use, and maintenance, of apparatus coming under each group of equipment—in order to ensure that all apparatus scheduled in the Regulations and sold after certain prescribed dates would be "interference-free." This course, furthermore, was favoured on the ground that the standards and procedure in the more difficult cases would not require to be defined until the specific technical groundwork was soundly laid. Procedure in making and applying regulations would thus be by stages.

13. Views of Committee.

The Committee arrived at the above-mentioned decision by a majority of 13 to 5, the majority including representatives speaking officially on behalf of the Incorporated Municipal Electrical Association and the British Electrical and Allied Manufacturers' Association.

14. Cost of effecting Suppression of Interference in Existing Apparatus.

Although the cost of correcting existing apparatus is undoubtedly higher than the cost involved if the apparatus is designed initially to be "interference-free," it has been found that the cost of effecting the required degree of suppression of existing apparatus or plant is usually but a small percentage of its original cost. Thus in the case of small apparatus it may amount to only a few shillings. For electric lifts in flats it will probably in many cases amount to £15–£25.

15. How Existing Apparatus has been dealt with.

In the large number of complaints with which the Post Office have dealt (now approximately 40 000 per annum) the cost of the suppression device has been paid for by the owner of the apparatus as a matter of goodwill on his part. But we are informed that a recent analysis shows that in some 4 or 5 per cent of the cases the owner has not been willing to meet the expenditure. In some of these cases the expenditure would doubtless amount to a sum which the owner does not feel he can afford.

16. Regulations in connection with Existing Apparatus.

The majority of the Committee hold the view that, where an undue amount of interference is being caused by existing apparatus and plant, i.e. installed before the date prescribed in the Regulations in respect of new apparatus, such apparatus also ought generally to be subject to regulations in respect of suppression equipment, use, and maintenance. The question of whether or no it would be right to compel the owner to defray the cost of correcting apparatus which he has purchased and was using before the enforcement of regulations is one of general ethics or of State policy which, in our opinion, only the legislature can decide.

The Committee make no recommendations on this issue but desire to draw attention to the following considerations:—

(*a*) It is most desirable that nothing proposed in this report, and no subsequent discussion or action in connection with it, should do other than encourage the goodwill shown by most owners in voluntarily correcting existing apparatus when they are made aware that it is causing interference.

(*b*) There must undoubtedly be some cases of interference from existing apparatus in which the owner cannot reasonably be expected to bear the cost of correction if the latter should be deemed essential.

(*c*) Where interference is caused by failure to maintain apparatus in good condition, the Committee consider that no hardship is involved in requiring an owner to attend to this maintenance.

(*d*) It should be pointed out that anyone installing apparatus that is likely to cause interference with radio reception in its vicinity may be expected, where reasonably possible, to equip such apparatus with suppression devices where such are readily available. If the owner has not taken such steps and it is ultimately found that undue interference is caused, the Committee consider that it would not be unreasonable that the owner should bear the cost of suppression, subject to suitable safeguards.

17. Conclusions.

Having given due consideration to all these questions, as regards both existing and new plant and apparatus, the Committee make the following recommendations as to the appropriate body for issuing Regulations and also as to the application of the Regulations to existing as well as to new apparatus.

18. RECOMMENDATIONS

The Electricity Commissioners should be given powers to issue Regulations to suppress interference with radio reception caused by both new and existing electrical appliances, plant, or machinery.

19.

The Commissioners would not issue any Regulations in respect of both new and existing apparatus or plant until after they had been satisfied:—

(i) that the apparatus or plant was causing undue interference;

(ii) that in the case of new apparatus it could without undue expense be altered in design or equipment so as to bring interference down to a satisfactory minimum; and

(iii) that in the case of apparatus already installed the interference caused could not be more easily eliminated by reasonable alteration of the receiving apparatus.

20.

The Electricity Commissioners should also have powers to make regulations as to the use of any electric appliances (both new and existing) which may cause interference with radio reception, including requirements as to the proper maintenance of all such appliances.

21.

The Commissioners should have power to require any scheduled apparatus sold after dates to be stated in the Regulations to bear a prescribed distinguishing Mark as a guarantee that it complied with the Regulations. This should, of course, apply to imported as well as to British-made apparatus.

22.

All interested parties should have an opportunity of applying for the issue or amendment of Regulations and of being heard before the Commissioners take action in regard to any specific apparatus.

23.

The Regulations in respect of the various classes of apparatus should either define the permissible limit of interference (as mentioned in paragraph 2), or, in particular cases, schedule the method which could be used to prevent interference.

24.

The Commissioners should also have powers to amend the Regulations from time to time in order that progress in the branches of the electrical industry affected may be fostered.

25.

The Commissioners should also have powers to hear and allow or disallow appeals against the application of the Regulations in particular cases.

26.

The Commissioners should be empowered to hold any Inquiries and institute such research as they may consider necessary for the purpose of carrying out the duties to be imposed upon them.

27.

The Commissioners may find it desirable to have an Advisory Committee, representative of the principal organizations concerned, to advise them on technical and other matters arising out of their duties under these proposals.

28.

The Post Office should have powers to enforce the application of the Regulations, subject to appeal to the Commissioners.

29.

Although the Committee consider that any recommendation as to meeting the cost of suppressing interference from existing apparatus is outside their province, nevertheless they recommend that where the Post Office ascertain, after complaints have been received, that undue interference is being caused to a substantial number of broadcast receivers by any equipment installed before the prescribed date (referred to in paragraph 21) and of a type scheduled in the Regulations, provision should be made which would enable the Commissioners to require such apparatus to be rendered interference-free within such time as may appear to them reasonable in respect of each particular type of apparatus, having regard to all the circumstances of the case.

30.

All costs incurred by the Commissioners in preparing and issuing the Regulations, and in carrying out any duties which may be imposed upon them, and all costs of the Post Office in investigating complaints and enforcing the Regulations, should be defrayed out of the quota of the Wireless Receiving Licence Fees which the Post Office retain.

31.

The Committee consider that where some appropriate body, other than the Electricity Commissioners, already have powers to require the suppression of interference (as exercised by the Ministry of Transport in connection with trolley-buses) no alteration of procedure is necessary, provided these powers are adequate. The Committee wish to emphasize, however, that, subject to proper safeguards, adequate powers should be given to some appropriate body to issue Regulations for the suppression of interference wherever it occurs.

APPENDIX I

Constitution of Committee.

The President (ex-officio).

C. C. Paterson, O.B.E. (Chairman)	nominated by the Council.
Lieut.-Col. A. G. Lee, O.B.E., M.C. (Vice-Chairman)	
J. M. Kennedy, O.B.E.	
F. W. Purse	
L. B. Turner, M.A.	

Body.	*Representative.*
Air Ministry	Capt. A. K. Toulmin-Smith, B.A.
Association of Consulting Engineers	Sir Arthur Preece
Association of Supervising Electrical Engineers	J. Munro
British Broadcasting Corporation	Sir Noel Ashbridge
British Electrical and Allied Industries Research Association	E. B. Wedmore
British Electrical and Allied Manufacturers' Association	C. Rodgers, O.B.E.
Central Electricity Board	Johnstone Wright
Electricity Commission	J. M. Kennedy, O.B.E.
E.R.A. Interference Sub-Committee	A. H. Bennett
Electrical Contractors' Association	H. Willoughby Ellis
General Post Office	Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.)
Incorporated Association of Electric Power Companies	J. M. Donaldson, M.C.
Incorporated Municipal Electrical Association	Major E. A. Barker, M.C.
International Electrotechnical Commission	P. Good
London Electricity Supply Association	R. S. Downe
Municipal Tramways and Transport Association	C. O. Silvers
National Physical Laboratory	F. M. Colebrook, B.Sc.
Provincial Electric Supply Association	T. A. Pond
Radio Manufacturers' Association	J. Joseph
Radio Society of Great Britain	J. Clarricoats
Railway Companies' Association	A. F. Bound H. Jones
Society of Motor Manufacturers and Traders	A. T. Priddle
Tramways, Light Railways and Transport Association	P. M. Hunt
Wireless Retailers' Association of Great Britain and Northern Ireland	A. E. Betambeau

Technical Secretariat: F. W. Endicott (British Broadcasting Corporation), W. D. Owen (Electrical Research Association), G. A. Struthers (General Post Office), and H. Wallis (Institution of Electrical Engineers).

APPENDIX II.

Investigations carried out and Work in Hand.

Sub-Committees.

At the first meeting of the Main Committee on Interference in June, 1933, it became evident that information would have to be collected as to the types of apparatus which formed the chief sources of interference, the best methods of reducing interference on the several types, and the cost of such methods. Four Sub-Committees were accordingly set up to deal with the following matters:—

Sub-Committee A:	Domestic apparatus, including refrigerators, fans, vacuum cleaners, etc.
Sub-Committee B:	Larger electric plant, including generators, motors, lifts, mercury rectifiers, etc.
Sub-Committee C:	Traction, including trolley-buses, tramways, and electric railways.
Sub-Committee D:	Automobiles and aircraft.

A further Sub-Committee (E) was subsequently set up to report on the effectiveness of the means (and the cost of such means) of dealing with interference apart from suppression at the source.

The Sub-Committees reported that methods were known which could be applied to the reduction of most forms of radio interference, and that the cost of such methods was, in general, but a small percentage of the cost of the interfering apparatus itself.

The above-mentioned Sub-Committees referred to the British Electrical and Allied Industries Research Association and to the General Post Office a number of investigations relating to the question of the suppression of interference due to:—

(*a*) Trolley-buses
(*b*) Electric lifts
(*c*) Mercury-arc rectifiers
(*d*) Ignition systems.

The E.R.A. and the G.P.O. prepared a number of reports based on their investigations, and the memoranda referring thereto have been circulated to the appropriate Committees and to the other interests concerned. A list of such Reports is given at the end of this Appendix.

There has been a very gratifying amount of co-operation amongst the various branches of the industry concerned, notably the British Broadcasting Corporation, the General Post Office, the Electrical Research Association, the B.E.A.M.A., and the various supply authorities and transport undertakings.

British Standard Specifications.

On the conclusion of the work of the I.E.E. Sub-Committees it was decided by the I.E.E. Main Committee that appropriate standard specifications should be prepared dealing with the components required for suppression devices, the standardization of a suitable measuring instrument for radio interference, and the defining of a Mark for use in " Radio-Interference-Free " apparatus At their request the British Standards Institution set up appropriate committees and the following Specifications have been issued or are now in course of preparation:—

(1) B.S.S. No. 613–1935, for Components for Radio-Interference Suppression Devices, was issued in June, 1935. This Specification gives the standard ratings for general components (condensers, resistors, and inductors or chokes) used in making up suppression devices for use with machines and appliances operated from supply mains of voltages not exceeding 500 (excluding traction equipment). Various ways of arranging such components are described in an Appendix, and a further Appendix gives some general indications of value of components which have been found satisfactory in practice.

Owing to the fact that there is a considerable disparity in the amount of suppression required on machines of the same type, but of different manufacture, in order to reduce the interference to reasonable dimensions, it was not found possible in this Specification to recommend definite values for components which would be suitable in all cases for each particular item, and some latitude in the choice of such components had to be given; a range of components is therefore given in the Specification in respect of each item.

(2) A Specification is in course of preparation for a measuring instrument which will be suitable for the measurement of interfering voltages. This Specification will describe the characteristics and performance requirements as recommended by the Special International Committee on Radio Interference (C.I.S.P.R.) and will also give detailed design particulars of a portable measuring set of convenient size and weight for use if required at works.

This testing set will enable manufacturers to ascertain what values of components should be used in order to reduce the amount of interference to prescribed limits and thus enable the apparatus to qualify for the " Radio-Interference-Free " Mark.

In certain types of interference the testing set may not be applicable and it will then be necessary to specify actual values of the components to be used for suppression.

(3) Specifications are also in hand for dealing with interference due to:—

(*a*) Trolley-buses and tramways
(*b*) Neon signs
(*c*) Ignition systems
(*d*) Electric lifts.

In the case of (*b*) and (*d*) these Specifications will be issued as Appendices to the Main Specifications dealing with the construction and operation of these two items.

(4) A further Specification will be put in hand as soon as the necessary information is available, setting out for the various classes of apparatus the permissible limits of interference which must not be exceeded in order to qualify for the Mark, and a definition of the " Radio-Interference-Free " Mark.

It is understood that the G.P.O. are arranging to carry out further tests on apparatus of various makes and to collect the necessary data in order to complete the above work. Through the co-operation of manufacturers and retailers a number of machines have already been tested in the G.P.O. and E.R.A. laboratories, but, owing to the magnitude of the task, manufacturers are being invited to co-operate in this work by permitting the necessary investigations to be carried out at their works.

International Electrotechnical Commission.

From the outset it appeared necessary in the interests of export trade to reach international agreement on the desirable degree of suppression and the method of measurement of interference, and, with this end in view, to co-operate with other countries in arriving at some agreed standard of the principles to be adopted in the measurement of interference and of the protection which it would be necessary to give to listeners in order that satisfactory reception of broadcast programmes might be possible.

An International Special Committee on Radio Interference (C.I.S.P.R.) was therefore set up by the I.E.C., and the first meeting was held in Paris in June, 1934. This was followed by meetings in Berlin and London.

The first practical step taken was to specify the requirements of measuring equipment which would be suitable for the measurement of interfering voltages. The apparatus in use in the various countries was compared. After various types of noise as heard on a loud-speaker were measured on a low-frequency measuring instrument, the C.I.S.P.R. specified the requirements of such an instrument which would give readings corresponding to the annoyance heard on a loud-speaker independently of the type of noise (continuous, impulsive, etc.).

The International Committee further recommended that, with a field strength of programme transmission of 1 mV/m modulated at 80 per cent, the level of disturbance should be at least 40 decibels below the peak values of the programme transmission.

The next step to be taken was to determine the maximum interfering voltage which could be tolerated at the terminals of a machine or appliance.

As the signal/interference ratio observed on receiving apparatus depends on:—

- (i) the radio-electric field of the wave received and on the wavelength;
- (ii) the coupling factor between the interfering source and the receiving apparatus;
- (iii) the interfering voltage created by the electrical machine or appliance;

a large number of tests were therefore carried out in this country and elsewhere on the effective height of listeners' aerials; the attenuation between the mains and the listener's aerial system; and the values of the interfering voltages from machines as measured at the terminals of the machines and also at the aerial–earth terminals of broadcast receivers. As a result of these tests and after consideration of the economic aspects of the problems involved, the technical experts appointed by the C.I.S.P.R. decided at their meeting in London in May, 1936, to recommend to the full International Committee that the values of the permissible interfering voltage at the terminals of machines should be reduced by progressive steps, values for long and medium waves being stated for immediate application, further lower values being recommended for adoption after a period of two years, and finally a common value for medium and long waves which it is desirable to adopt as early as possible in order to protect the largest percentage of listeners consistent with the limitations imposed by technical and economic considerations.

The values to be adopted for Great Britain as a result of the above international work still remain to be decided.

List of E.R.A. Reports.

M/T27:—" Simple Apparatus for Comparative Observations of Radio Interference produced by Electrical Appliances."

M/T28:—S. WHITEHEAD and W. NETHERCOT: " The Suppression of Short-Wave Radiations from Automobile Ignition Systems."

M/T29:—S. WHITEHEAD and L. H. DANIEL: " The Suppression of Broadcast Interference from Trolley Buses."

M/T30:—" Some Considerations in the Measurement and Suppression of Radio Interference."

M/T39:—S. WHITEHEAD and L. H. DANIEL: " The Magnitude of the Radio-Frequency Disturbance from Trolley Buses, and the Use of Condensers and other Devices in its Suppression."

M/T42:—S. WHITEHEAD and L. H. DANIEL: " The Suppression of Broadcast Interference from Electric Lifts."

M/T44:—W. NETHERCOT and W. D. OLIPHANT: " The Properties and Performance of the E.R.A. Short-Wave Receiver for Field-Strength Measurements."

M/T45:—S. WHITEHEAD and L. H. DANIEL: " Methods of Measurement of Radio Interference."

List of G.P.O. Documents and Publications.

Post Office Electrical Engineers' Journal.

P. L. BARKER and A. H. MUMFORD: " A Field-Strength Measuring Set using Thermal Agitation Noise as the Calibrating Source," 1935–36, vol. 28, p. 40.

A. C. WARREN: " Broadcast Interference Investigation. Post Office Radio Service," 1935–36, vol. 28, p. 23.

Institution of Post Office Electrical Engineers.

A. S. ANGWIN: Paper No. 137: " Interference with Wireless Reception arising from the Operation of Electrical Plant," 1932.

Telephone and Telegraph Journal.

A. S. ANGWIN: " Electrical Interference with Broadcasting," 1933, vol. 19, p. 200.

P.O. Radio Branch, Interim Report.

" Interference with Wireless Broadcast Reception by Tramway and Trolley-Bus Systems," November, 1935.

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" Suppression of Radio Interference."
" Good Wireless Reception."
" Electrical Interference."

P.O. Radio Reports. (Not printed for publication.)

No. 178. " The Investigation of Interference by Electric Lifts with Broadcast Reception."

No. 179. "The Investigation of Interference by High-Frequency Electrical Therapeutical Apparatus with Broadcast Reception."

No. 192. "The Investigation of Interference by Mercury-Arc Rectifiers with Broadcast Reception."

No. 201. "Measurements of Impedance of a Heavy-current H.F. Choke at Broadcasting Frequencies."

No. 202. "The Further Investigation of Interference by Electric Trolley-Bus Systems with Broadcast Reception."

No. 216. "Further Measurements on H.F. Choke Coils for the Prevention of Interference by Trolley-Buses with Broadcasting."

No. 255. "Measurement of the Interference from the Portishead–Bridgwater 132 kV Overhead Power Line."

No. 277. "Some Considerations relating to the Measurement of Radio Interfering Effects."

No. 295. "Measurement of the Impedance at Radio Frequencies of Post Office Units, Condenser."

No. 300. "Further Considerations relating to the Measurement of Radio Interfering Effects."

No. 318. "Interference with Broadcast Reception caused by a Steel-Tank Grid-controlled Mercury-Arc Rectifier."

No. 321. "Theoretical and Practical Comparison of High- and Low-Frequency Methods of Measurement of Radio Interference."

No. 332. "Comparison of the German Standard Radio-Interference Measuring Equipment and the British Post Office Portable Measuring Set."

No. 346. "Prevention of Interference by Electro-Medical Apparatus with Broadcast Reception."

W2. 187A. "Comparison of the E.R.A. and G.P.O. Radio-Interference Measuring Sets."

Journal of the Institution of Electrical Engineers.

A. Morris: "Interference of Electrical Plant with Reception of Radio Broadcasting," 1934, vol. 74, p. 245.

Wireless World.

A. Morris: "Electrical Interference. The Problem of a Definition," 1934, vol. 35, p. 59.

A. Morris: "The Technique of Radio Interference," 1934, vol. 35, p. 445.

Electrical Power Engineer.

J. Neale: "Broadcast Interference," 1935, vol. 17, p. 510.

Electrician.

"Trolleybuses—Methods of suppressing Radio Interference," 1936, vol. 116, p. 482.

MAGNETIC CHARACTERISTICS OF NICKEL-IRON ALLOYS WITH ALTERNATING MAGNETIZING FORCES[*]

By EDWARD HUGHES, Ph.D., D.Sc., Member.

(*Paper first received* 24*th September*, 1935, *and in final form* 4*th January*, 1936.)

SUMMARY

The magnetic properties of thin mumetal and permalloy "C" laminations have been determined with sinusoidal alternating magnetizing forces, and it has been found that for magnetizing forces of the order for which the d.c. permeability is a maximum, the a.c. permeability at, say, 50 cycles per sec. may be less than a tenth of the corresponding value with direct current; whereas for comparatively large magnetizing forces the a.c. and d.c. permeabilities are practically identical.

The a.c. flux densities were determined by (*a*) a mechanical rectifier, (*b*) a cathode-ray oscillograph, and (*c*) the Maxwell and the Campbell bridges. Also, by means of the cathode-ray oscillograph, B–H loops were obtained at various frequencies up to 75 cycles per sec. It is shown that these loops become more elliptical as the frequency is increased; but it is pointed out that this is not due to the flux at a given point of the lamination becoming more sinusoidal, but to the average effect of a flux varying enormously in density and in phase over the section of the lamination.

The method given in textbooks for calculating the mean flux density in thick iron laminations due to an alternating magnetizing force assumes the permeability to remain constant at a value equal to the maximum d.c. permeability. It is shown in this paper that such a method accounts for only a small fraction of the difference between the densities obtained with alternating and direct current; and it is suggested that a much closer estimate of the a.c. flux density may be made by using the differential permeability derived from the d.c. hysteresis loops instead of the maximum d.c. permeability.

A peculiar dissymmetry was observed in the B–H loops obtained with alternating magnetization, this dissymmetry being most marked when the maximum magnetizing force was in the neighbourhood of that corresponding to maximum d.c. permeability. The dissymmetry was perfectly stable but could be reversed by the momentary application of a comparatively large magnetizing force. It could not be reversed by reducing the flux to zero and increasing it again to the original value. No explanation has been found for this phenomenon.

The iron loss at 50 cycles per sec. was measured by the Maxwell and the Campbell bridges, and was found to vary approximately as the 1·7th power of the maximum flux density over a very considerable range of the latter.

It is shown that although the impedance of an iron-cored choke may be balanced by a resistance and inductance in series in the Maxwell bridge, the flux linkages per ampere and, therefore, the maximum flux density for the same number of turns, may be far smaller for the equivalent inductance than for the actual choke; and the method usually given for calculating the maximum flux density for iron-cored chokes from Maxwell-bridge tests may be in considerable error. It is also shown that values of maximum flux density based upon the equivalent impedance, instead of the equivalent reactance, are in reasonably close agreement with those determined with the cathode-ray oscillograph. Further, the values thus calculated from the Maxwell-bridge results are in agreement with those obtained with the Campbell bridge.

INTRODUCTION

It is well known that the maximum d.c. permeability of nickel-iron alloys may exceed 100 000. These alloys, however, are almost invariably employed in a.c. circuits, so that the variation of flux density with alternating current is of much greater practical importance than the corresponding relationship with direct current.

All the a.c. tests referred to in this paper were made with sinusoidal current. Owing to the high cost of nickel-iron alloys, test specimens are usually small, and owing to their high permeability it is seldom necessary to work with a magnetizing force exceeding 0·4 oersted. The p.d. across the primary winding is, therefore, very small; and the necessity of inserting a suitable current-measuring device in series with the primary renders it practically impossible to apply a sinusoidal voltage across that winding. On the other hand, when a sinusoidal supply voltage is available it is possible to ensure almost a perfect sinusoidal current by merely connecting a high non-inductive resistance in series with the primary.

One advantage of using a sinusoidal primary current is that the maximum magnetizing force can be calculated from $(4\pi/10)(I_pT_p/l) \times 1\cdot414$, where I_p is the effective value of the primary current, T_p is the number of primary turns, and l is the mean length of the specimen. It is realized that such procedure may be open to objection in view of the fact that for nickel-iron alloys the current and the flux do not usually attain their maxima at the same instant (see B–H oscillograms of Figs. 6, 8, and 9). On the other hand, there seems no reason to doubt that at the surface of the laminations the two quantities do reach their maxima simultaneously. Before some of the factors discussed in the paper were appreciated, attempts were made to estimate the wave-form of the demagnetizing m.m.f. due to the eddy currents, but it was subsequently realized that such calculations were entirely fictitious and therefore valueless so far as the definition of the maximum magnetizing force was concerned. After the experimental work described in this paper had been nearly completed, a paper[†] was published by Webb and Ford in which the same method of calculating the maximum magnetizing force was adopted.

Particulars of Specimens and Coils.

(A). Mumetal ring, consisting of 30 stampings, each $7\frac{1}{16} \times 6\frac{1}{16} \times 0\cdot015$ in., shellac-varnished on both sides

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] "A.C. Permeability and the Bridge Method of Magnetic Testing," *Journal I.E.E.*, 1935, vol. 76, p. 185.

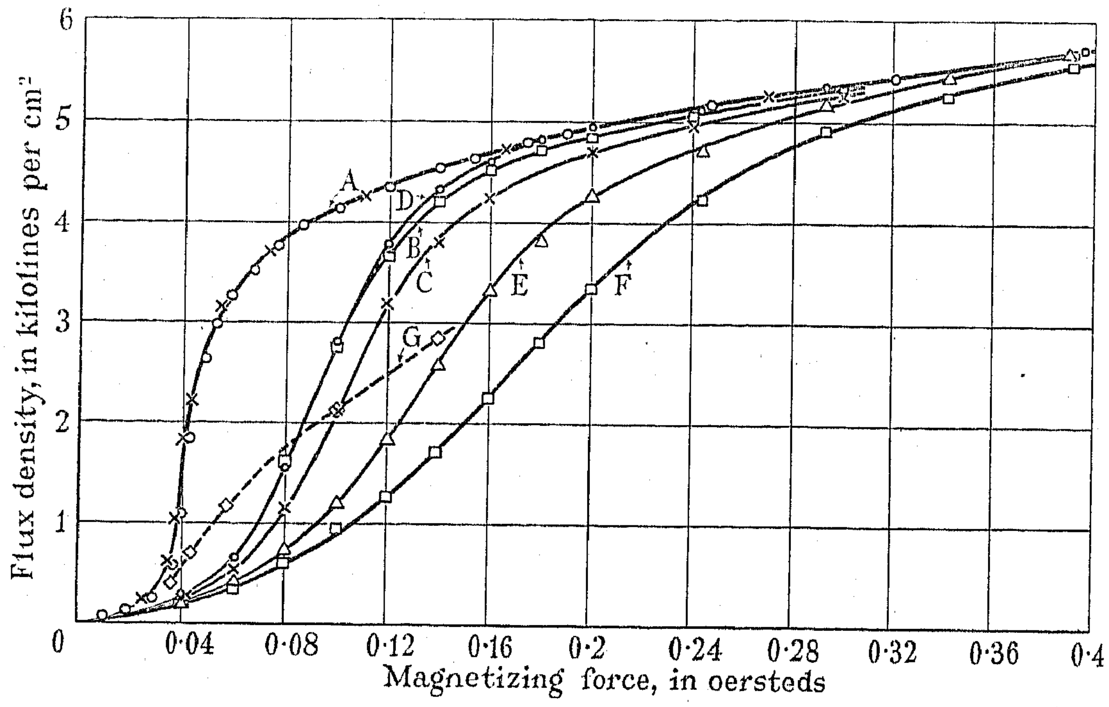

Fig. 1.—Comparison of d.c. and a.c. permeabilities on 0·015-in. mumetal laminations.

Curve A.—D.C. results, o—o for increasing *H* and x—x for decreasing *H*.
Curve B.—A.C. results with mechanical rectifier, 21 cycles per sec.
Curve C.—A.C. results with mechanical rectifier, 30 cycles per sec.
Curve D.—A.C. results with oscillograph, 20·6 cycles per sec.
Curve E.—A.C. results with oscillograph, 50 cycles per sec.
Curve F.—A.C. results with oscillograph, 75 cycles per sec.
Curve G.—Calculated flux densities, 50 cycles per sec. (Table 2).

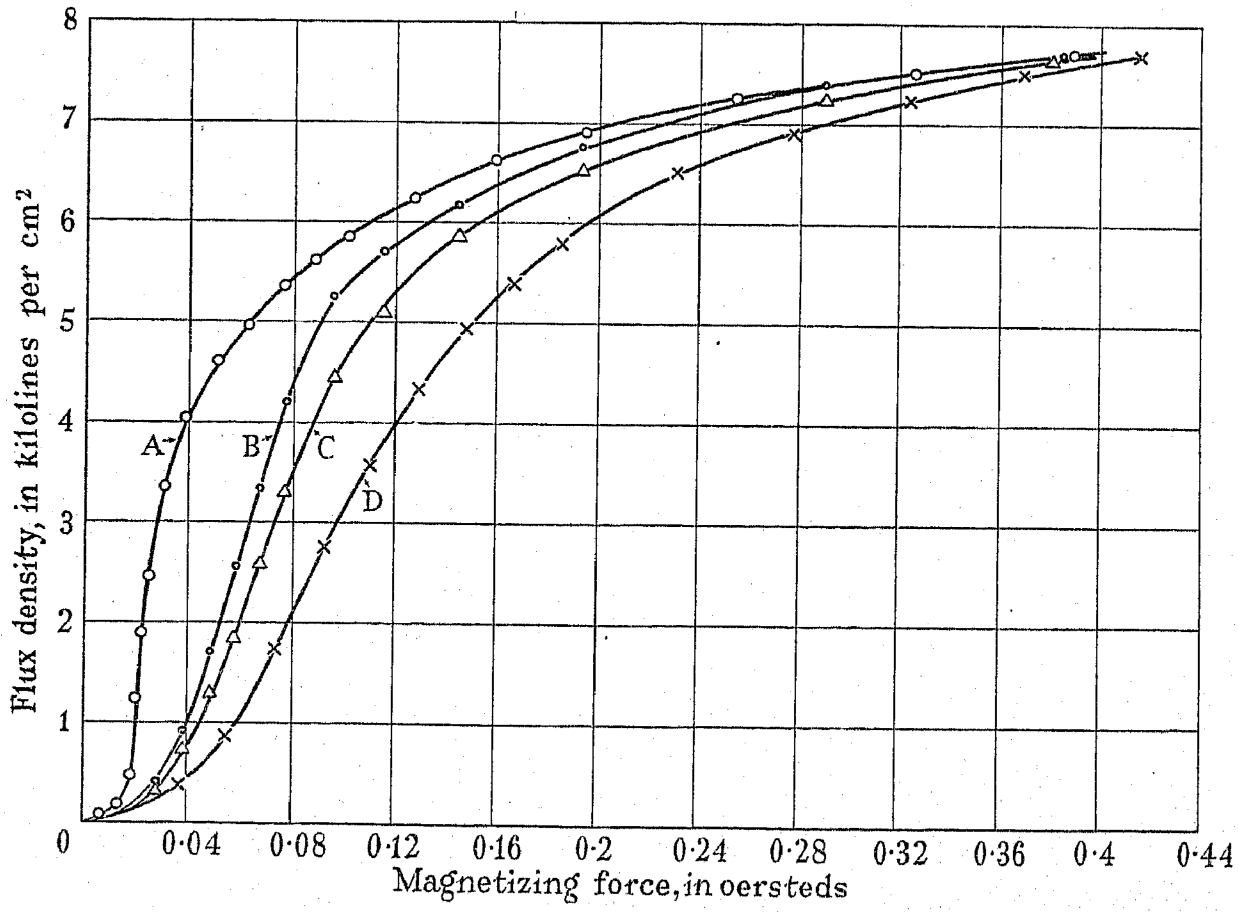

Fig. 2.—Comparison of d.c. and a.c. permeabilities on 0·014-in. permalloy " C " laminations.

Curve A.—D.C. results.
Curve B.—A.C. results with mechanical rectifier, 21 cycles per sec.
Curve C.—A.C. results with mechanical rectifier, 30 cycles per sec.
Curve D.—A.C. results with oscillograph, 50 cycles per sec.

before assembly. Sectional area of iron = 1·452 cm^2; mean periphery of ring = 52·4 cm. Primary winding: 670 turns of thick flexible cable, wound uniformly over the specimen, having a d.c. resistance of 0·092 ohm. Secondary winding: 670 turns of No. 30 S.W.G. copper wire, wound as uniformly as possible. The assembled laminations were loosely wrapped with several layers of cotton tape before the winding was put on, every precaution being taken to avoid subjecting the mumetal to mechanical strains.

Another mumetal specimen, consisting of only 6 stampings, was very carefully wound and tested to discover whether certain unexpected characteristics of the larger specimen were due to any strains to which it might have been accidentally subjected and whether they were affected by the number of laminations. As the results were almost the same for the two specimens, no further reference is made to the smaller specimen.

(B). Permalloy " C " ring, consisting of 6 stampings, each $3 \times 2\frac{1}{16} \times 0\cdot014$ in. (approx.). Sectional area of iron = 0·253 cm^2; mean periphery = 20·2 cm. The laminations, interleaved with thick paper rings, were assembled in an annular ebonite trough which was then filled with cotton wool, loosely packed, and covered with an ebonite ring. Primary winding: 21 turns of thick flexible cable, uniformly wound. Secondary winding: 878 turns of No. 28 S.W.G. copper wire, wound as uniformly as possible.

Tests.

The tests referred to in this paper may be grouped thus:—

(*a*) D.C. tests.
(*b*) A.C. tests with (1) a mechanical rectifier,
  (2) a cathode-ray oscillograph,
  (3) the Maxwell and the Campbell bridges.

DIRECT-CURRENT TESTS

The specimens were demagnetized with alternating current, and the *B–H* relationship was derived first with increasing values of *H* and then with decreasing values. The results are represented by curves A in Figs. 1 and 2. With permalloy " C," it was found that the flux densities were practically the same for decreasing as for increasing values of *H*; whereas with mumetal there was quite an appreciable difference at the lower portion of the curve. The tests were repeated several times with quite consistent results.

For purposes of comparison with results obtained with alternating current, a number of hysteresis loops were taken on specimen " A " and these have been plotted in Fig. 3.

ALTERNATING-CURRENT TESTS WITH MECHANICAL RECTIFIER

An inspection of the d.c. characteristics gave the impression that a sinusoidal primary current would be accompanied by a very distorted e.m.f. wave; and as the secondary voltages available did not exceed about 10 volts it was impossible to measure the mean voltage by means of a thermionic valve or a copper-oxide rectifier. A synchronous commutator was not available, but a very effective substitute was found by driving, by means of a d.c. motor B (Fig. 4), a 2-part rectifier of the secohmmeter type, connected as shown. By this means the secondary circuit, consisting of a winding S, a pivoted centre-zero moving-coil galvanometer G, and a high resistance *r*, was closed during half a revolution of the rectifier. The latter was run at approximately synchronous speed, and the speed of the d.c. motor was adjusted by means of a potentiometer C until the galvanometer pointer oscillated very slowly, when it became a simple matter to note the maximum deflection. The demagnetizing ampere-turns of the secondary were negligible compared with the primary ampere-turns.

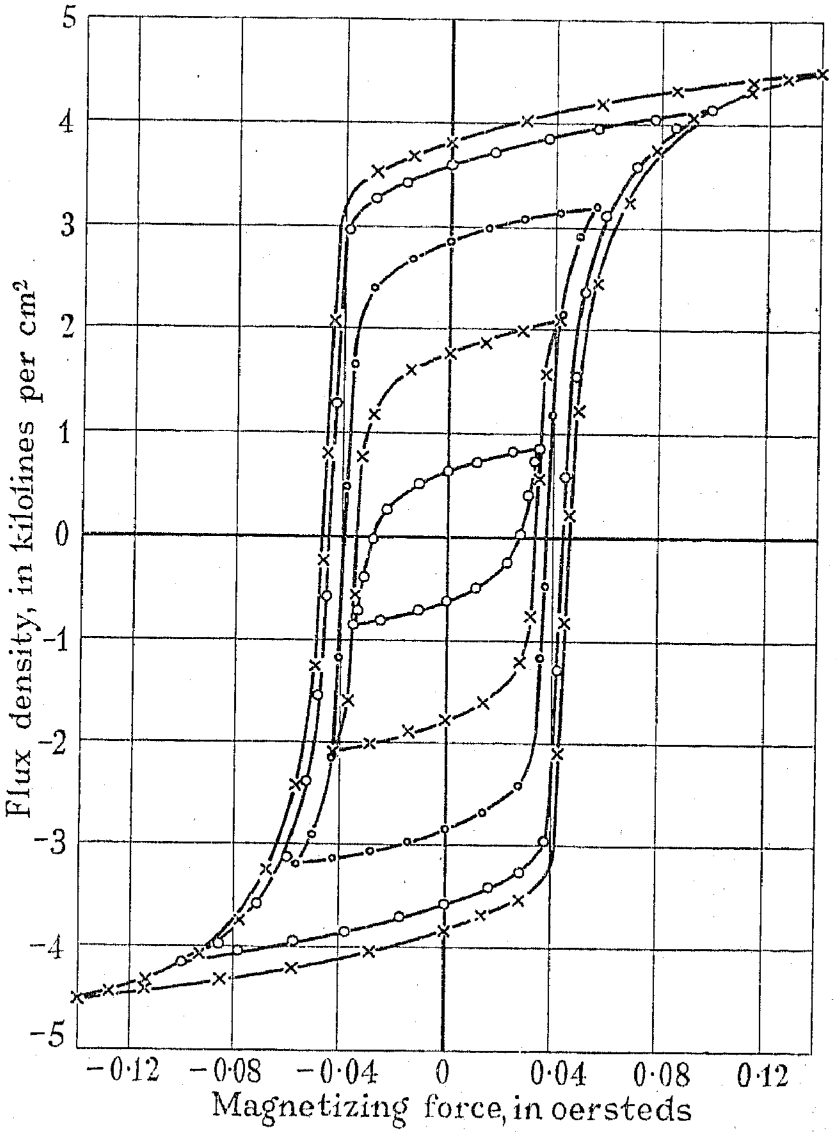

Fig. 3.—D.C. hysteresis loops on 0·015-in. mumetal laminations.

The galvanometer was calibrated in terms of average voltage by substituting for S a low variable resistance connected in series with an air choke to the a.c. supply and noting the maximum galvanometer deflections for various sinusoidal voltages.

From the mean value of the secondary e.m.f. and the effective value of the primary current, the maximum flux density and the maximum magnetizing force respectively were calculated. These tests were carried out at 21 and 30 cycles per sec., and the results are represented in Figs. 1 and 2. At frequencies above about 35 cycles per sec. the rectifier did not function satisfactorily.

In view of the very large discrepancy between the d.c. and a.c. results for values of *H* in the region of maximum d.c. permeability, the accuracy of the instruments and of the method was checked by tests on an air-core mutual inductance. In this case the d.c. and a.c. results were found to be in very close agreement. The above-mentioned discrepancy was confirmed by tests made with a cathode-ray oscillograph and described in the next section.

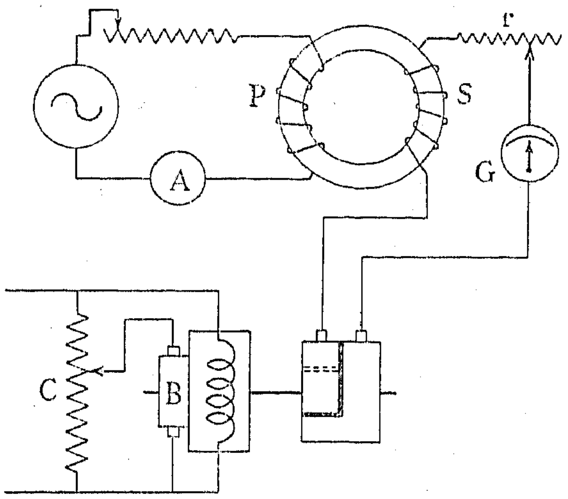

Fig. 4.—Circuit for a.c. permeability measurement with mechanical rectifier.

ALTERNATING-CURRENT TESTS WITH CATHODE-RAY OSCILLOGRAPH

The wave-form of the secondary e.m.f. was observed by means of a cathode-ray oscillograph fitted with a time-base unit, and was found to be unsymmetrical over the range of magnetizing force corresponding to the discrepancy between the d.c. and a.c. permeabilities referred to in the preceding section, the maximum dissymmetry coinciding roughly with the maximum discrepancy. This dissymmetry appeared more as an inequality in the duration of the positive and negative half-waves than in the apparent shape of the two halves, the wave-form being somewhat similar to curve E in Fig. 10. The time base did not seem sufficiently accurate to justify the analysis of the e.m.f. waves obtained therewith, and it was found better to employ the circuit shown in Fig. 5 and obtain polar oscillograms of primary current and secondary e.m.f. Fig. 6 shows a few typical examples of such oscillograms for the mumetal specimen at 50 cycles per sec. In all these oscillograms, deflection due to the magnetizing force is along the horizontal axis.

It was thought at first that as the dissymmetry in these *E–H* loops always appeared in the same direction, it must be due to the polarizing effect either of direct current or of the earth's magnetic field. The first possibility was ruled out by inserting condensers in the four leads between the oscillograph and the primary and secondary circuits, by supporting the H.T. source of the oscillograph on wax, etc. Also, a tertiary winding was put on the ring and connected through a large choke and a variable resistance to a battery. This direct current was adjusted to make the loop approximately symmetrical, but the m.m.f. required was far greater than anything that could be accounted for by leakage in the primary and secondary circuits. The effect of the earth's field was tried by holding the specimen in various positions relatively to that field and by placing it inside a mumetal shield, but no effect could be observed. The author has shown elsewhere* that the flux through such a specimen due to the earth's field is in all cases negligibly small. Further, a strong permanent magnet had to be brought fairly near to the specimen to produce any appreciable effect on the shape of these *E–H* loops.

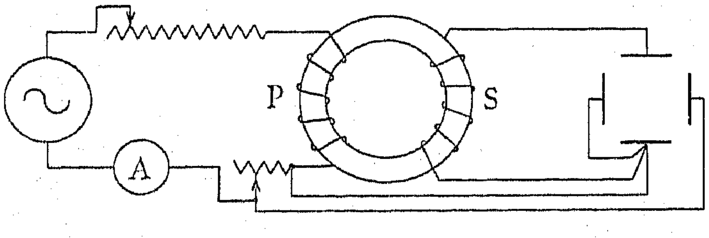

Fig. 5.—Circuit for obtaining *E–H* oscillograms.

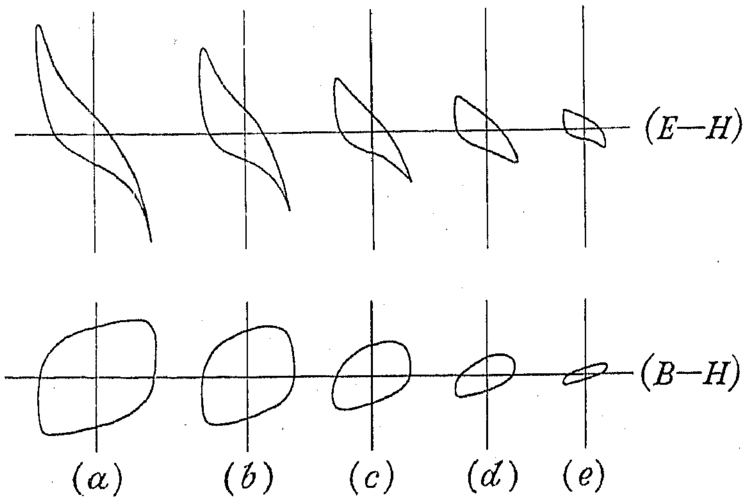

Fig. 6.—*E–H* and *B–H* oscillograms for 0·015-in. mumetal laminations at 50 cycles per sec. Values of $H_{max.}$:—(*a*) 0·2; (*b*) 0·17; (*c*) 0·14; (*d*) 0·11; (*e*) 0·08.

After the author had spent a considerable time searching for the cause of this apparent polarization, he happened to short-circuit a resistance in the primary circuit, and to his surprise the loop appeared with the dissymmetry reversed. It was then found that the momentary application of a comparatively large current might result in the reversal of the loop. On the other hand, the reduction of the m.m.f. to zero by means of a potentiometer followed by an increase to the original value *never* resulted in a reversal. Further, the unsymmetrical loop is perfectly stable and the primary current can be switched

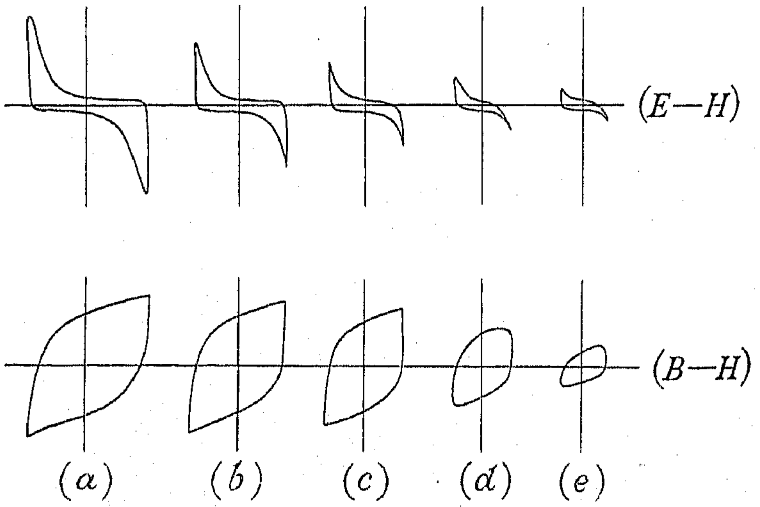

Fig. 7.—*E–H* and *B–H* oscillograms for 0·015-in. mumetal at 20·6 cycles per sec. Values of $H_{max.}$ as in Fig. 6.

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* *Electrician*, 1934, vol. 113, p. 463.

on and off indefinitely without the shape of the loop being appreciably altered.

It can be shown[*] that if the secondary winding be connected across a circuit consisting of a high resistance in series with a condenser of relatively low reactance, the instantaneous voltage across the condenser is directly proportional to the flux linkages in the secondary, and the amplitude of the voltage across the condenser is therefore proportional to the maximum flux density in the iron.

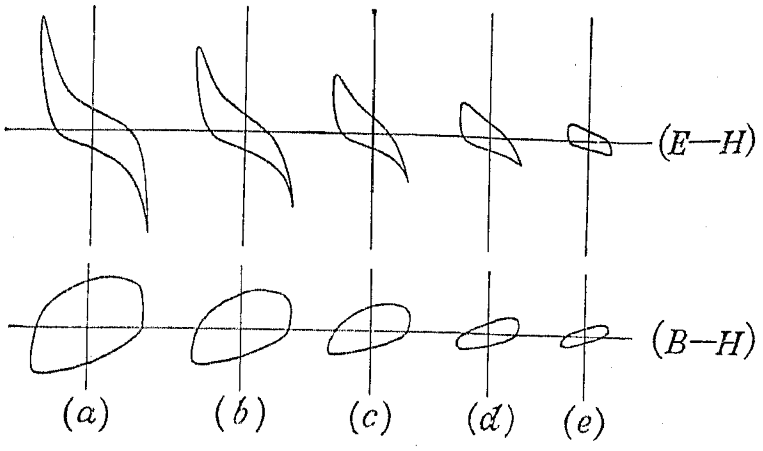

Fig. 8.—*E–H* and *B–H* oscillograms for 0·015-in. mumetal at 75 cycles per sec. Values of $H_{max.}$ as in Fig. 6.

The secondary of the mumetal specimen was connected across a 0·121-μF condenser in series with a resistance of 1 megohm, and the p.d. across the condenser was applied, via a single-stage resistance-capacitance amplifier, to the top and bottom plates of the oscillograph. The linearity of the amplifier had already been checked. The side plates were connected across a non-inductive resistance in the primary circuit. In this way the hysteresis loops of Fig. 6 were obtained.

By applying known sinusoidal voltages across the condenser and the 1-MΩ resistance, the vertical axis of the oscillograph was calibrated in terms of the maximum flux density in the specimen. Thus, if k be the flux linkages per mm of deflection on the vertical axis and if d mm be the deflection when a sinusoidal voltage having an effective value V and frequency f is applied; then

$$\text{Maximum flux linkages} = \frac{V \times 10^8}{4 \cdot 44 f} = kd$$

Hence k can be determined; and the maximum flux densities calculated from vertical deflections obtained with various values of $H_{max.}$ are represented by curve E in Fig. 1.

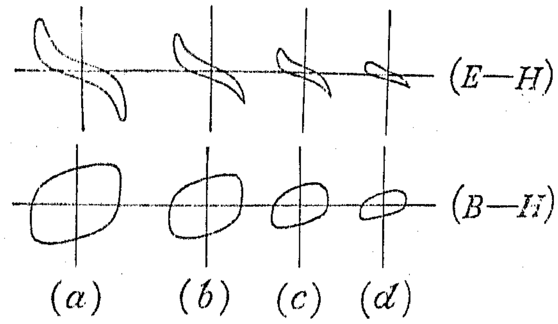

Fig. 9.—*E–H* and *B–H* oscillograms for 0·014-in. permalloy "C" at 50 cycles per sec. Values of $H_{max.}$:—(*a*) 0·148; (*b*) 0·12; (*c*) 0·0925; (*d*) 0·074.

This test was repeated at 20·6 and at 75 cycles per sec. A selection of the *E–H* and *B–H* oscillograms is given in Figs. 7 and 8, and the flux densities are represented by curves D and F respectively in Fig. 1.

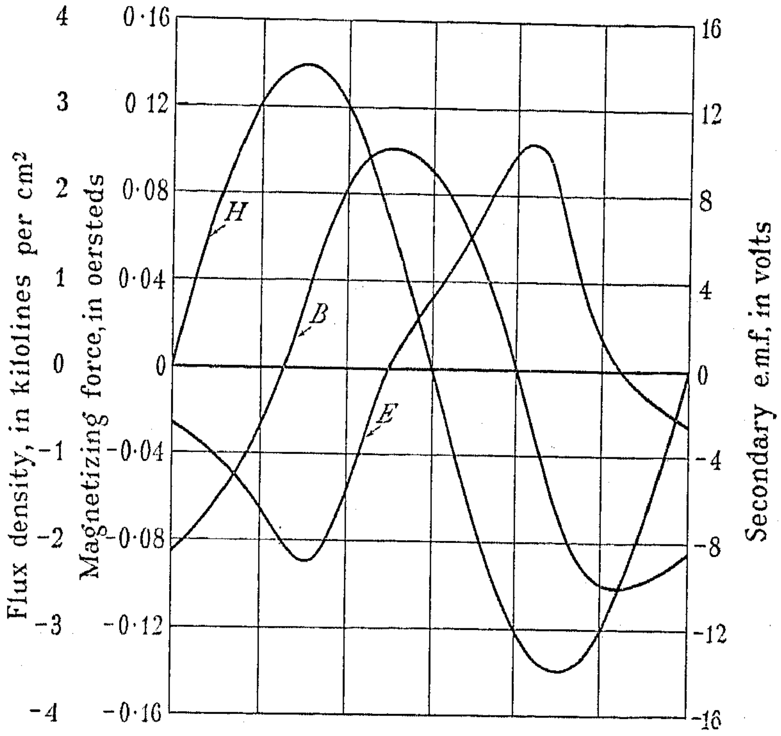

Fig. 10.—Wave-forms of *H*, *E*, and *B*, for 0·015-in. mumetal laminations for $H_{max.} = 0 \cdot 14$ at 50 cycles per sec.

Fig. 9 shows the *E–H* and *B–H* oscillograms obtained at 50 cycles per sec. on permalloy "C," and the corresponding variation of maximum flux density with maximum magnetizing force is represented by curve D in Fig. 2.

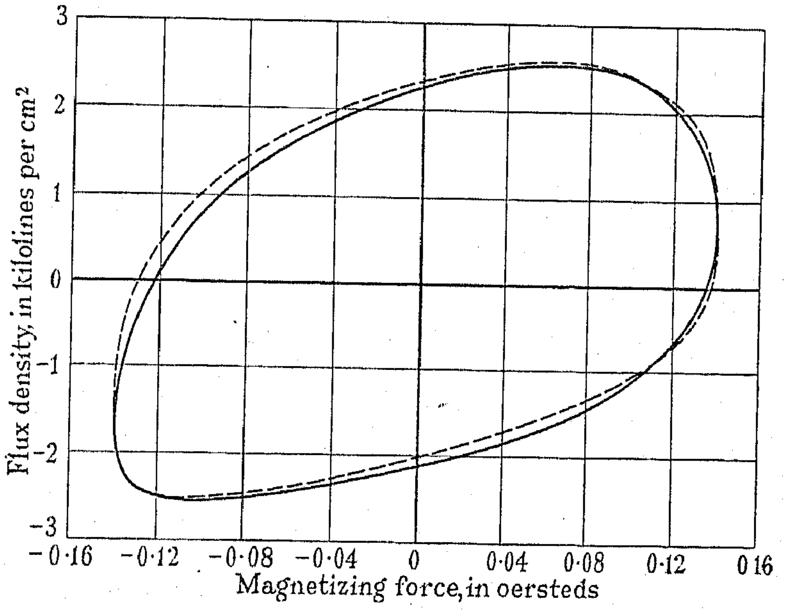

Fig. 11.—*B–H* curves.
——— Derived from *E–H* oscillogram.
– – – – Enlarged *B–H* oscillogram, Fig. 6 (*c*).

It was felt desirable to check the agreement between the *E–H* and the *B–H* loops and at the same time to derive the wave-forms of e.m.f. and of flux. The dissymmetry in the case of the mumetal specimen operating at 50 cycles per sec. appeared most pronounced when the peak magnetizing force was about 0·14 oersted; consequently, oscillograms for this condition were taken for comparison.

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[*] C. R. Cosens: *Wireless Engineer*, 1935, vol. 12, p. 190.

Owing to the induced e.m.f. being proportional to the rate of change of flux, the dissymmetry of the E–H loop is far more pronounced than that of the B–H loop, so that the former was taken as the starting-point, and the wave of e.m.f., E in Fig. 10, was derived from the E–H loop of Fig. 6(c) for a sinusoidal magnetizing force having a maximum value of 0·14 oersted. From the data given for the mumetal specimen it follows that

$$\text{Induced e.m.f.} = e = -670 \times 1{\cdot}452 \times (dB/dt) \times 10^{-8}$$
$$\therefore dB = -0{\cdot}103 \times 10^{6} \times e\,dt$$

The total change of flux density between the positive and negative crests of flux was found to be 5 046 lines per cm^2. From the B–H oscillograms it appeared that the two peaks of flux were at least approximately equal. On the assumption of equal peaks, the curve of flux density, B in Fig. 10, was plotted from a large number of values of $\int e\,dt$. By noting corresponding values of B and H in Fig. 10 the full-line polar curve of Fig. 11 was derived; and for purposes of comparison the corresponding B–H loop, obtained experimentally, is shown dotted. It will be seen that the agreement is sufficiently good to confirm the reliability of the oscillograms.

DISCUSSION OF THE ABOVE RESULTS

(1) The discrepancy between the d.c. and a.c. permeabilities

In the paper of Webb and Ford, referred to on page 213, similar discrepancies, but of much smaller magnitude, are shown for 0·4-mm lohys sheets at 50 cycles per sec. and for 0·3-mm stalloy sheets at 500 cycles per sec. The authors state that "when the a.c. permeability fell below the d.c. value, $B_{max.}$ lagged behind $H_{max.}$ by an amount roughly proportional to the difference between the permeabilities," and "suggest strongly that these differences are due mainly, if not entirely, to eddy currents." They do not, however, attempt to explain why this discrepancy should only appear for values of $H_{max.}$ corresponding roughly to the maximum d.c. permeability. Also, Gall and Sims in a recent paper* give three loops obtained by Ewing on a solid steel bar. These loops are so pertinent to the present discussion that they have been reproduced in Fig. 12. Cycle (a) was performed very slowly, while (b) and (c) were taken at increased frequency. It is seen that the maximum density decreases and the loop becomes more elliptical as the frequency is increased. The authors add: "It is of much interest to search for this effect in samples of laminated material, where, though necessarily smaller, it may still be in evidence." It is hardly necessary to point out the great similarity between Ewing's loops and the various B–H loops given in this paper.

Gall and Sims suggest that Ewing's loops "indicate a reduction of flux harmonics with rise of frequency," and point out that "the ellipse is associated with sinusoidal quantities of only one frequency." Upon this hypothesis they proceed with a mathematical analysis of elliptic permeability. It is extremely doubtful, however, whether such an analysis does anything more than cover up the facts rather than help to elucidate them, since it does not deal with the phenomena which modify the shape of the loop.

It is generally agreed that the decrease of maximum flux density with increase of frequency is due to the presence of eddy currents, and a method of calculating the average flux density is given in a number of textbooks. For instance, Steinmetz* shows that the average density over the section of a lamination is given by

$$B_a = \frac{B_1}{\sqrt{2cl}}\sqrt{\left[\frac{\cosh 2cl - \cos 2cl}{\cosh 2cl + \cos 2cl}\right]} \quad . \quad . \quad (1)$$

where B_1 = flux density at surface of lamination,
l = half thickness of lamination, in cm,
$c = 10^{-4} \times 1{\cdot}984\sqrt{\left[\frac{\mu f}{\rho}\right]}$
μ = permeability, assumed constant,
f = frequency,
and ρ = specific resistance.

For the mumetal laminations, $l = 0{\cdot}01905$ cm, $\rho = 42$ microhms per cm cube, and μ = (say) 60 000, namely the maximum d.c. permeability, this being the value employed by Steinmetz and other authors who supplement their proof with an example. Then, for f = (say) 30 cycles per sec.,

$$c = 41{\cdot}1$$
$$\text{and } B_a = 0{\cdot}902\,B_1$$

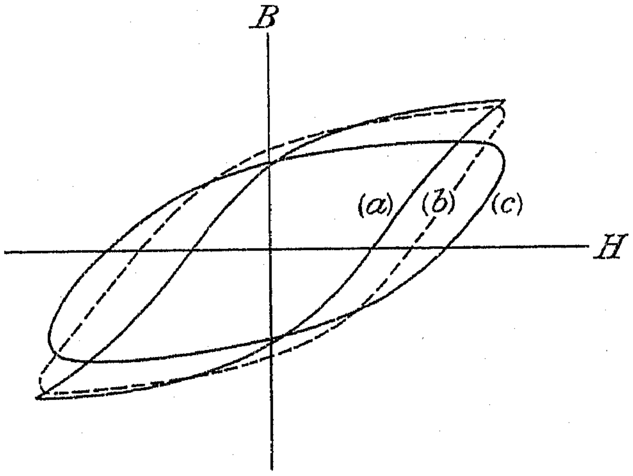

Fig. 12

A comparison of this value with the results given in Fig. 1 shows that the theory, as usually interpreted, does not account for more than 12 per cent of the decrease in flux density observed experimentally. Consequently, it is natural to ask whether there is any justification for assuming the permeability (1) to remain constant, (2) to be that corresponding to $B_{max.}/H_{max.}$; and to both questions the answer is in the negative.

It is evident that if the magnetizing force be increased from OC to OD in Fig. 13, the change of flux density is CE + DF; and the average differential permeability† over this range is $(CE + DF)/CD$, a value that is far greater than $B_{max.}/H_{max.}$, even when this corresponds to the maximum d.c. permeability.

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* "On the Theory and Measurement of the Magnetic Properties of Iron," *Journal I.E.E.*, 1934, vol. 74, p. 453.

* "Transient Phenomena," 3rd ed., p. 365.

† "Differential permeability" at any point of a magnetization curve is defined by Spooner in "Properties and Testing of Magnetic Materials" (p. 10) as the slope of the tangent to the magnetization curve at that point, and is employed here to represent dB/dH on the hysteresis loop.

Webb and Ford did not give hysteresis loops for the specimens tested by them; but from the magnetization curves given in their Figs. 2 and 3 it is possible to estimate that the maximum differential permeability may be as high as 40 000. As a matter of interest, the ratio of the average to the surface density, i.e. B_a/B_1 in equation (1), has been calculated for differential permeabilities of 20 000 and 40 000 respectively, and the results are given in Table 1. Specific resistances of 60 and 40 microhms per cm cube were assumed for stalloy and lohys respectively.

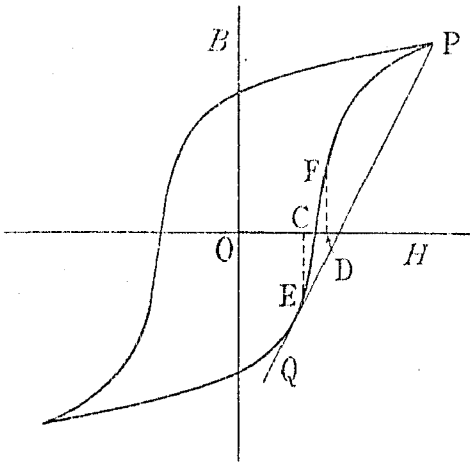

Fig. 13

A comparison of these results with those given in Figs. 2 and 3 of Webb and Ford's paper shows that they are of the right order of magnitude and do give an indication of the circumstances under which the divergence between the d.c. and a.c. permeabilities begins to be appreciable.

If the same method be applied to the mumetal specimen whose loops are given in Fig. 3, it is estimated that the maximum differential permeability is about 700 000; and the corresponding average flux density at 30 cycles per sec. is only 0·263 × the surface density, while at 50 cycles per sec. the ratio is reduced to 0·204. Comparison with Fig. 1 shows that even these figures do not fully account for the observed decrease of flux density.

Table 1

Material	Frequency	Differential permeability	Average density / Surface density
0·3-mm stalloy . .	50	20 000	0·993
,, ,, . .	50	40 000	0·973
,, ,, . .	500	20 000	0·665
,, ,, . .	500	40 000	0·44
0·4-mm lohys . .	50	20 000	0·953
,, ,, . .	50	40 000	0·852

As an indication of the complexity of the problem, it may be pointed out that, on the assumption of constant permeability, the flux density B_0 at the centre of the lamination is given[*] by

$$B_0 = \frac{1\cdot414\,B_1}{\sqrt{[\cosh 2cl + \cos 2cl]}}$$
$$= 0\cdot0634 \times \text{surface density, for mumetal specimen at 50 cycles per sec., assuming } \mu = 700\,000.$$

Also, the corresponding phase difference between the flux at the centre and that at the surface of the lamination is cl radians, namely 198° in the above example.

These figures are sufficient to show the enormous variation in magnitude and in phase of the flux density over the section of the lamination; and since this variation is further complicated by considerable variation of the differential permeability it is evident that an exact calculation of the ratio of the a.c. to the d.c. flux density for a magnetizing force corresponding roughly to the maximum d.c. permeability becomes practically impossible.

So far, only the maximum discrepancy between the a.c. and the d.c. permeabilities has been considered. It was thought desirable, however, to see whether a comparatively simple method could be devised to enable an approximate estimate of the a.c. flux density to be made. Thus, it appeared reasonable to assume that the maximum flux density would be largely influenced by the average differential permeability just before the magnetizing force reached its maximum; and as a simple measure of this average differential permeability it was decided to take the slope of PQ in Fig. 13, where PQ is a tangent to the d.c. hysteresis loop. By applying this method to the hysteresis loops of Fig. 3 and assuming a frequency of 50 cycles per sec., columns 3 and 4 of Table 2 were calculated.

Table 2

$H_{max.}$	$B_{max.}$ from d.c. test	Differential permeability (= slope of PQ)	Calculated $B_{max.}$ with a.c.	Actual $B_{max.}$ with a.c.
0·14	4 520	$7\cdot48 \times 10^4$	2 830	2 570
0·099	4 160	$11\cdot25 \times 10^4$	2 120	1 180
0·0565	3 200	$23\cdot0 \times 10^4$	1 140	370
0·0424	2 080	$27\cdot2 \times 10^4$	681	240
0·0355	860	$13\cdot85 \times 10^4$	396	190

The values of flux density in the fourth column have been inserted in Fig. 1, and it would appear that for densities above 2 500 the difference between the calculated and the measured values of B is comparatively small. It may be argued that as there is still considerable difference between the two sets of values in the region of maximum d.c. permeability, the method just suggested is of little practical value. On the other hand it may be pointed out that even in the worst case the method does account for more than 70 per cent of the decrease in flux density.

(2) Dissymmetry of the *B–H* loop

No explanation has been found for this peculiar phenomenon. It appears to be perfectly definite for both mumetal and permalloy "C." An attempt was made to see whether it occurred with sinusoidal applied voltage, the oscillograph deflection corresponding to the H-axis being produced by a coil of very low impedance in series with the primary of the specimen. The B–H loops thus obtained had the same characteristic dissymmetry and, as before, the E–H loops showed the dissymmetry in an accentuated form, though the shape was somewhat different. Also, the dissymmetry could be reversed by the momentary application of a relatively large voltage, but never by reducing the voltage to zero and increasing it again to the original value. The latter fact seems to indicate that the B–H loop closes slightly above or below the origin. The magnitude of such displacement may be extremely small but just sufficient to bias the shape of the loop when the magnetizing current is increased.

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[*] STEINMETZ, *loc. cit.*

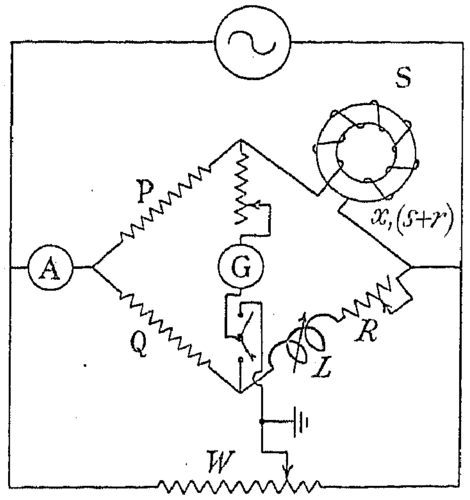

Fig. 14

ALTERNATING-CURRENT TESTS WITH THE MAXWELL AND CAMPBELL BRIDGES

The methods described earlier in this paper are not adaptable for determining the iron loss; and as the specimens were small it was decided to do this by means of (*a*) Maxwell's bridge, and (*b*) Campbell's bridge.* Also, it has already been shown that the B–H loops for nickel-iron alloys are roughly elliptical. Consequently, if the magnetizing force be a sinusoid, the flux wave cannot be greatly distorted. It was therefore thought that by assuming sinusoidal waves it would be possible to calculate, from results obtained from bridge tests, values of maximum flux density which would be in fair agreement with the actual values already determined by means of the cathode-ray oscillograph.

The tests were made at a frequency of 50 cycles per sec., a vibration galvanometer being used as a detector. An excellent sinusoidal voltage was available, and in the case of the Campbell bridge a sinusoidal magnetizing current was assured by connecting a high resistance in series with the primary. With the Maxwell bridge the same condition was approximated by using non-inductive resistances of 3 000 ohms for each of the two arms P and Q in Fig. 14. The reactance of L, with the bridge balanced, never exceeded 5 ohms, and the resistance of the galvanometer circuit was not reduced below 1 000 ohms. The wave-form of the magnetizing current through S was checked on an oscillograph, but no departure from a sine wave could be detected, even with the maximum magnetizing force employed.

The ammeters available were of the moving-iron type; consequently it was found more satisfactory to connect them as in Fig. 14 rather than insert them in series with S. A non-inductive resistance W was found to give freedom from earth currents.

Iron Loss.

The iron losses were calculated in the orthodox manner, and the iron loss per cm³ has been plotted against $H_{max.}$ in Figs. 15 and 16. It is seen that the results obtained with the Campbell and the Maxwell bridges agree very

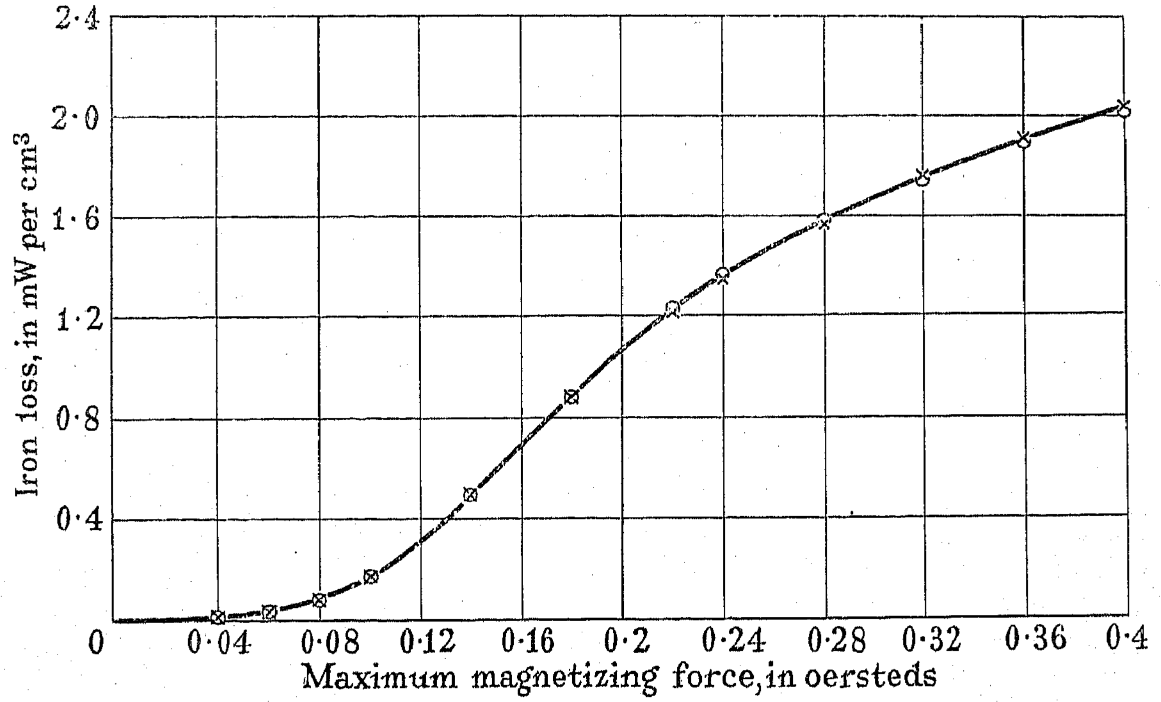

Fig. 15.—Iron loss for 0·015-in. mumetal, 50 cycles per sec.

X With Campbell bridge.
⊙ With Maxwell bridge.

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* A. Campbell: *Proceedings of the Physical Society*, 1910, vol. 22, p. 207; also C. E. Webb and L. H. Ford: *Journal I.E.E.*, 1935, vol. 76, p. 185.

closely. It is usual to plot the iron loss as a function of the flux density, but the variable permeability of the iron renders unreliable any flux density calculated from the bridge results. Consequently, the relationship between the iron loss and the flux density has been determined by plotting in Fig. 17 the logarithm of the iron loss against that of the maximum flux density derived from Figs. 1 and 2 for the same maximum magnetizing force. The straight lines drawn through the two sets of readings correspond to an exponent of 1·7 for the flux density and will be seen to represent about the best mean in each case; hence, for both mumetal and permalloy " C,"

$$\text{Iron loss} \propto B_{max.}^{1\cdot 7}$$

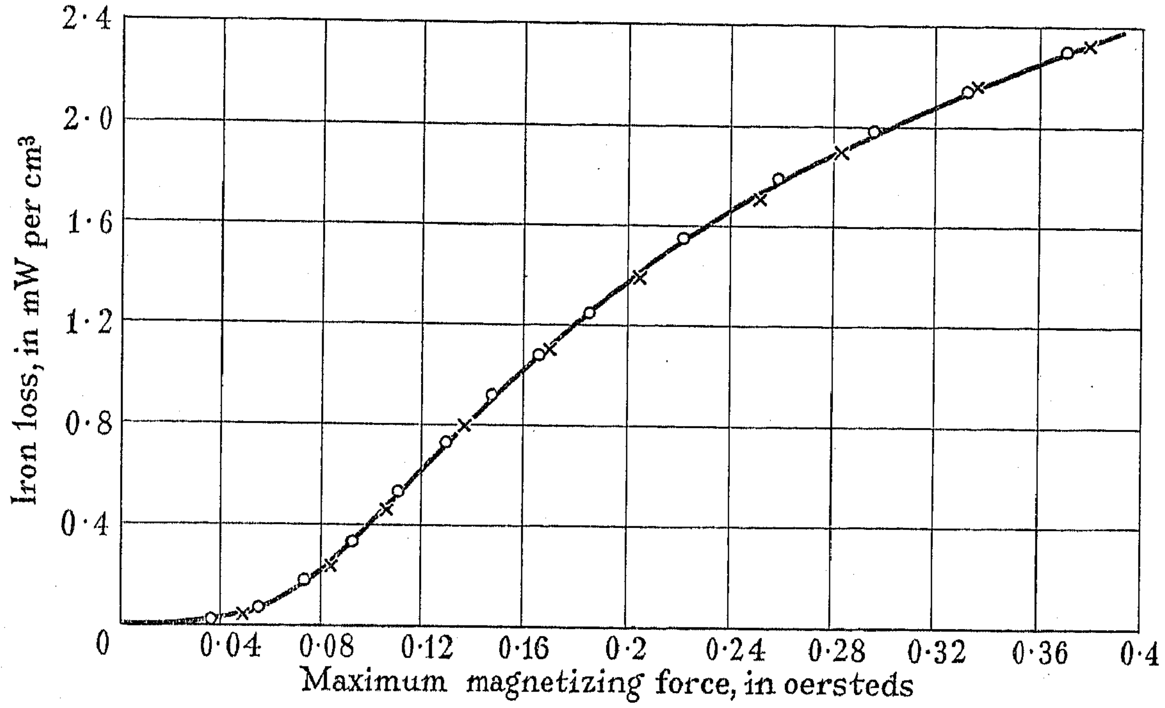

Fig. 16.—Iron loss for 0·014-in. permalloy " C," 50 cycles per sec.

× With Campbell bridge.
⊙ With Maxwell Bridge.

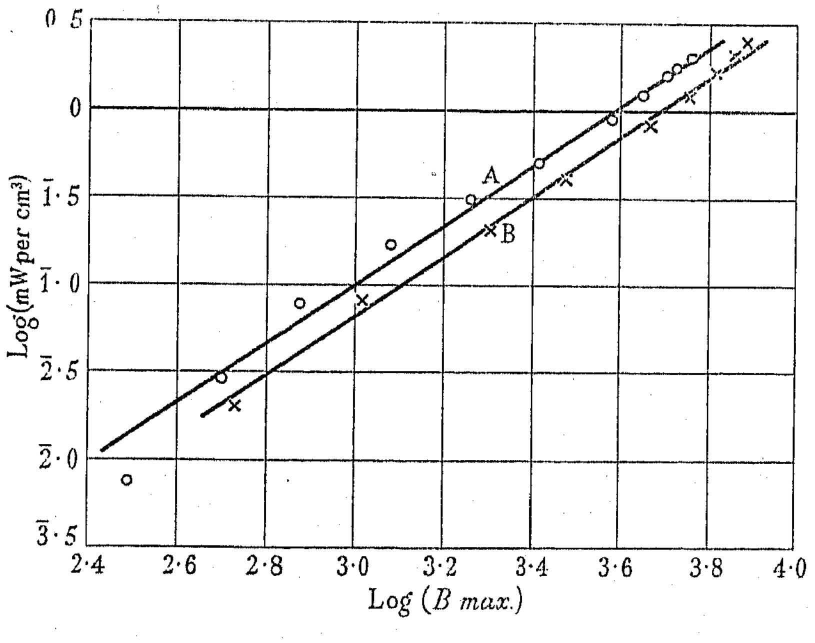

Fig. 17.—Variation of iron loss with flux density.

Curve A.—For 0·015-in. mumetal.
Curve B.—For 0·014-in. permalloy " C."

Flux Density.

For the Campbell bridge the method of calculation was that employed by Webb and Ford[*] and not that suggested in textbooks.[†] The latter method makes the assumption that the current and the induced e.m.f. are in quadrature, an assumption that may be satisfactory for ordinary iron but is not justified in the case of nickel-iron alloys, as will be evident from data given later in the discussion of the Maxwell bridge.

Let I = effective value of primary current,
R and M = primary resistance and mutual inductance, respectively, to balance the bridge,
T_s = number of secondary turns on specimen,
and a = sectional area of iron.

Then $I\sqrt{[R^2 + (\omega M)^2]} = 4\cdot 44 T_s f a B_{max.} \times 10^{-8}$

The values of $B_{max.}$ thus calculated for the mumetal specimen have been plotted in Fig. 18; and the corresponding values of $B_{max.}$ derived from the cathode-ray oscillograph tests, described above, have also been added for comparison.

For the Maxwell bridge the method first employed for calculating $B_{max.}$ was that given in textbooks[‡] dealing with the application of this bridge to iron testing. Thus when the bridge shown in Fig. 14 is balanced with $P = Q$, then

$$r + s = R; \text{ and } x = L,$$

where r = an equivalent resistance such that the loss in it due to a current I is equal to the iron loss,
s = resistance of winding,
and x = equivalent inductance of winding.
If T = number of turns on S,
and $I_{max.}$ = maximum value of current through S,

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[*] *Loc. cit.*

[†] For instance, "Dictionary of Applied Physics," vol. 2, p. 502; Golding's "Electrical Measurements," p. 364; Spooner's "Properties and Testing of Magnetic Materials," p. 318.

[‡] *Loc. cit.*; also Hund's "High-Frequency Measurements," p. 314.

it appears customary to take

$$x = \text{flux linkages per ampere in specimen} \times 10^{-8}$$

$$= \frac{B_{max.}aT}{I_{max.}} \times 10^{-8}$$

$$\therefore\ B_{max.} = \frac{LI_{max.}}{aT} \times 10^{8}$$

The results calculated from this expression are represented by curve C in Fig. 18. It is seen that the values may be less than one-half the corresponding values obtained with the cathode-ray oscillograph and with the Campbell bridge. The permalloy "C" specimen gave similar results.

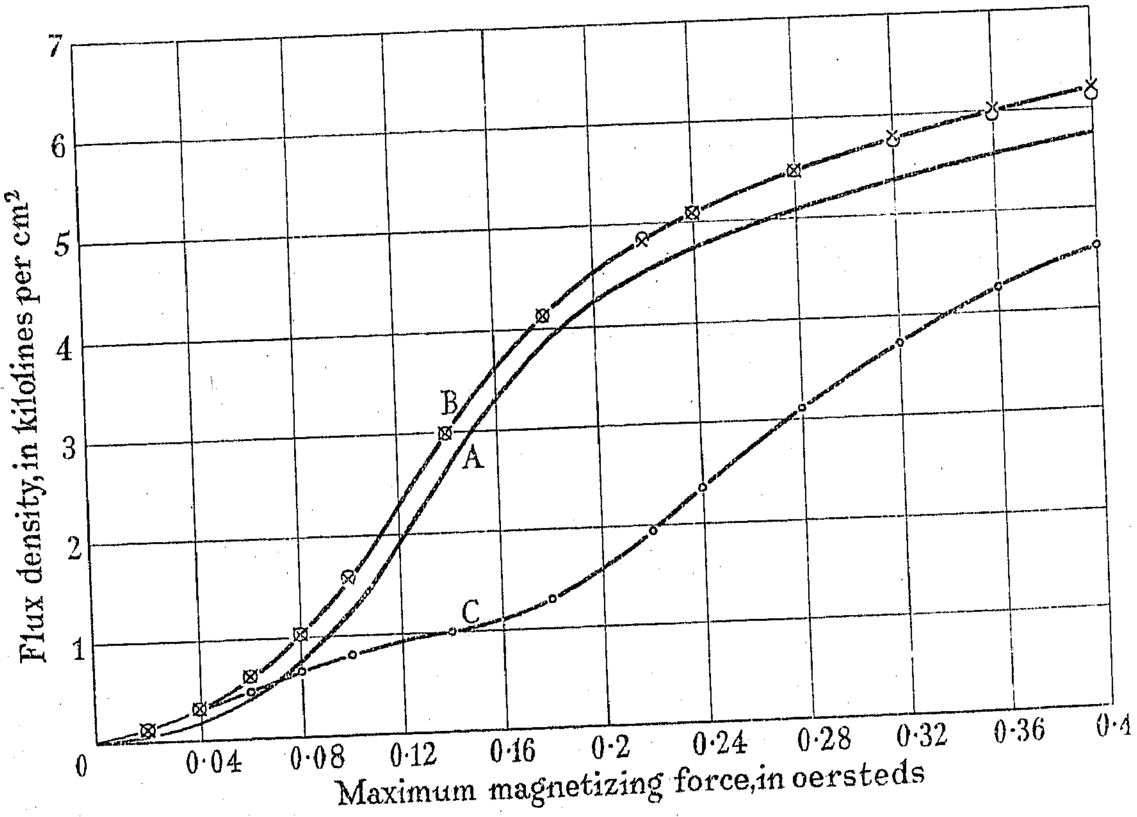

Fig. 18

Curve A.—From cathode-ray oscillograph.
Curve B.—X with Campbell bridge; ⊙ with Maxwell bridge.
Curve C.—From equivalent inductance in Maxwell bridge.

Suppose the instantaneous value of the magnetizing force to be represented by

$$H = H_{max.} \sin \omega t$$

then, assuming the elliptical relationship between the magnetizing force and the flux density, the latter is represented by

$$B = B_{max.} \sin (\omega t - \phi)$$

where ϕ is the angle of lag of the flux behind the magnetizing current, as in Fig. 19. Hence, the component of the applied voltage to neutralize the induced e.m.f. leads the current by $(90^\circ - \phi)$.

$$\text{But} \quad V = 4{\cdot}44Tf\Phi \times 10^{-8}$$

$$= \sqrt{2}\pi Tf\Phi \times 10^{-8} \quad . \quad . \quad . \quad . \quad (2)$$

$$\text{Also,} \quad V = I\sqrt{[r^2 + (\omega x)^2]} \quad . \quad . \quad . \quad . \quad (3)$$

Suppose Φ' to be the maximum flux corresponding to a current I amperes (r.m.s.) through an inductance x wound with T turns on a non-metallic core and therefore having no eddy-current or hysteresis loss; then

$$x = \frac{\Phi' T}{\sqrt{2}I} \times 10^{-8}$$

If $B_{max.}$ and $B_{max.}$ be the maximum flux densities corresponding to Φ and Φ' respectively, then, from the above equations,

$$\frac{B'_{max.}}{B_{max.}} = \frac{\Phi'}{\Phi} = \frac{\omega x}{\sqrt{[r^2 + (\omega x)^2]}} = \sin (90^\circ - \phi)$$

$$\therefore\ B_{max.} = B_{max.} \cos \phi$$

To get some idea of the possible numerical relationship between these two quantities, the flux-density curve of Fig. 10, namely that for mumetal subjected to $H_{max.}$ of 0·14, was analysed and its fundamental component found to be

$$B = 2\,580 \sin (\omega t - 64^\circ\, 18')$$

$$\therefore\ B^{max.} = 2\,580 \cos 64^\circ\, 18' = 1\,145.$$

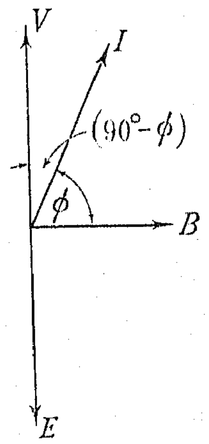

Fig. 19

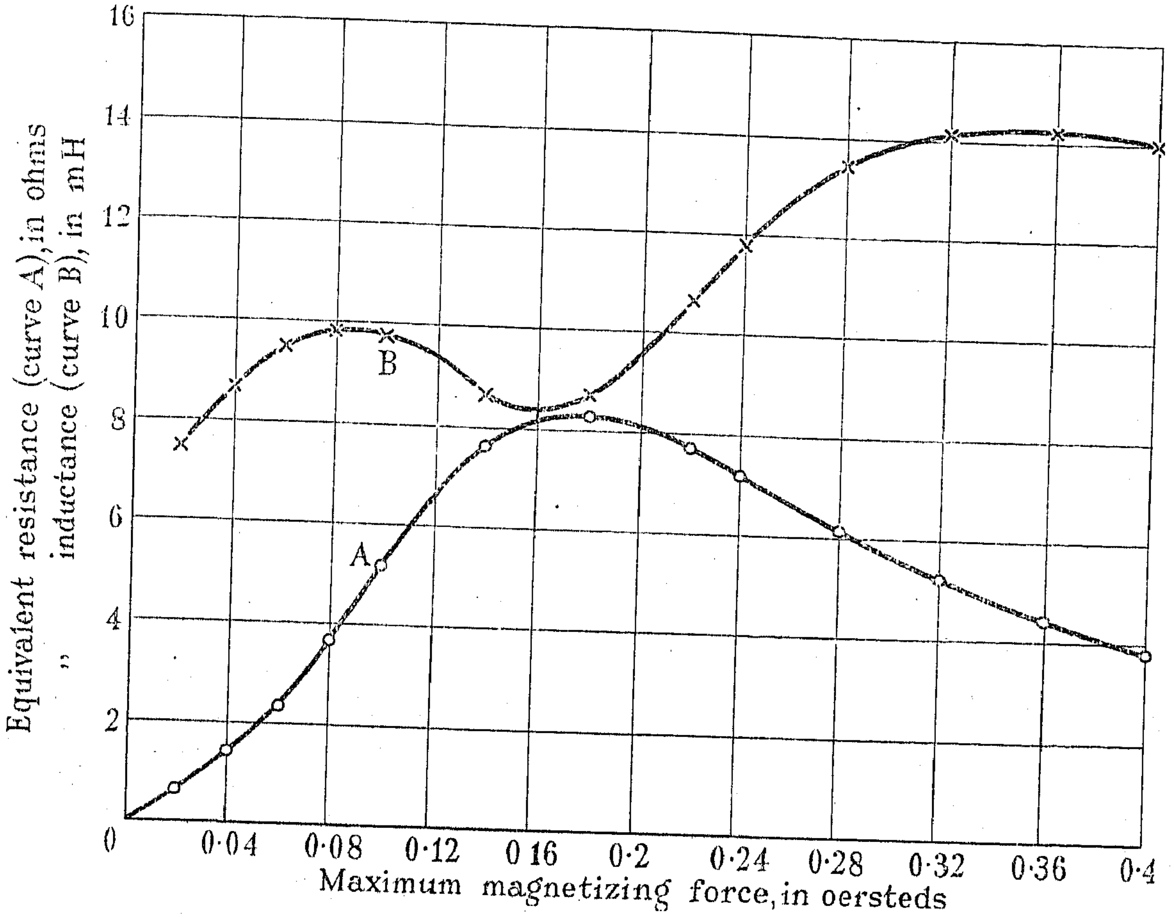

Fig. 20

This figure compares favourably with the value, 1 020, given by curve C in Fig. 18.

From equations (2) and (3) the following expression for $B_{max.}$ can be derived for the Maxwell bridge when P and Q are equal:—

$$B_{max.} = \frac{I\sqrt{[(R-s)^2 + (\omega L)^2]}}{4\cdot 44Tfa} \times 10^8$$

The flux densities, calculated in this way for the mumetal specimen, are represented by circles in Fig. 18 and will be seen to agree with those given by the Campbell bridge and to agree as closely as might reasonably be expected with the actual values measured with the cathode-ray oscillograph.

From Fig. 18 it will be noticed that the maximum difference between curves B and C occurs for values of $H_{max.}$ in the region of maximum permeability, and it is interesting to note how rapidly the relative value of the equivalent resistance and inductance varies in this region. Fig. 20 shows these quantities in the case of mumetal. Similar variations were experienced with permalloy " C."

The author desires to express his gratitude to the Principal and Governors of the Technical College, Brighton, for facilities to carry out the experimental work described in this paper.

DISCUSSION ON "THE ACTION OF A SPLIT-ANODE MAGNETRON"*

Messrs. H. Awender and **D. M. Tombs** (Germany) (*communicated*): In working with a G.E.C. valve CW 10, a split-anode magnetron of dimensions of the same order as that of the authors, we have obtained curves showing that in our experiments the oscillation intensity of waves between 2 and 8 metres is not related to the anode cut-off point, as the authors state in the last paragraph on page 463 (vol. 78).

A typical photographic record of the relationship between three variables—anode-current I_a, magnetic field H, and high-frequency intensity I_{hf}, is reproduced in Fig. A. The registering apparatus (details of which are shortly to be published) enables a third variable to be shown by the length of a diagonal line, the bottom point of which traces the usual two-variable curve. In this case the anode current is plotted vertically, the magnetic field intensity horizontally, and the rectified high-frequency current as the third variable. It will be seen that the maximum high-frequency current is obtained in the neighbourhood of the top bend, and a smaller current is developed farther down the curve, in contradiction to the author's statement mentioned above. The wavelength was 8 metres, and the anode voltage 800.

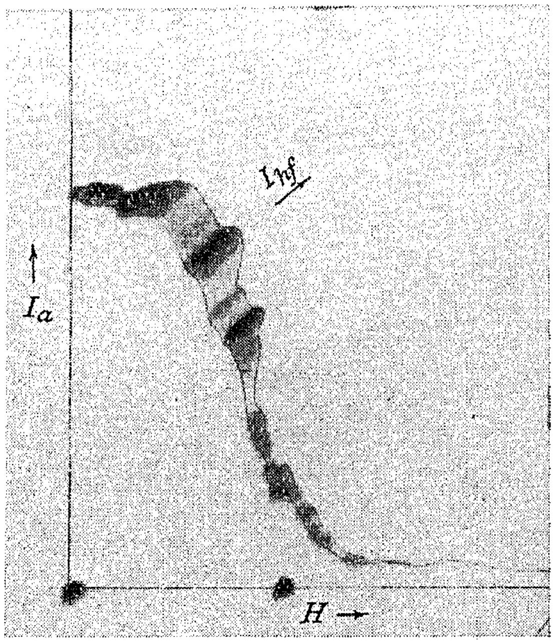

Fig. A

In regard to Fig. 7, a set of photographic records of a similar nature have been obtained. It has been found that points for a given wavelength on the V/H curve at which the maximum high-frequency energy occurs (and after which oscillation ceases) lie on a straight line through the origin, although the wavelength was considerably shorter than that at which the authors were working, and within the range where deviation was expected. Further, the slope of these lines was also found to be proportional to the wavelength. From the data available the constant in the equation $\lambda = k(H/V)$ was approximately 3·25.

Mr. E. C. S. Megaw (*communicated*): The authors have set themselves the problem of accounting for the "amplified" negative resistance which a split-anode magnetron is found to exhibit at a wavelength proportional to H/V, where H is the magnetic field strength and V is the anode supply-voltage. Their explanation is that the spirals which individual electrons describe about the lines of magnetic force "precess" round the axis of the anode; and that, when the oscillation period is equal to the time of precession from the neighbourhood of one anode gap to the next, electrons which just fail to reach the anode segment having (instantaneously) the lower potential, on their first approach, succeed in doing so one or more half-cycles later. The important factor, according to this view, is the distribution of conduction current between the anode segments; the essential mechanism is thus the same as that of the long-wave "dynatron" oscillations.

This explanation fits the facts well as far as it goes, but it does not appear to go far enough. It cannot, for example, account for conversion efficiencies in excess of the ratio of peak to mean anode voltage, which have been found to exist in many cases when the ratio H/V has the optimum value for the wavelength generated. This and other results† have led me to conclude that in the optimum condition many electrons reach the anode with velocities less than those corresponding to the instantaneous potential difference between the anode and cathode at the moment of arrival. It is probable that both the distribution of electrons between the anode segments and the change of electron energy which can take place during transit through a rapidly changing electric field must be taken into account in explaining the "amplified" negative resistance.

The authors have not been able to derive a theoretical expression for the optimum wavelength, corresponding to the empirical relation $\lambda = k(H/V)$. The following derivation may be of interest.

To reduce the problem to the simplest possible terms, it is assumed (1) that the magnetic field strength H is large compared with the critical field strength at which cut-off occurs in the absence of oscillations, and (2) that the oscillation amplitude is small compared with the mean anode voltage. We have to find how long an electron will take to travel from the neighbourhood of one anode gap to that of the next. Under the conditions assumed, this electron will move through a nearly constant and almost purely radial electric field. The tangential velocity of precession will therefore be nearly

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* Paper by Messrs. E. W. B. Gill, B.Sc., M.A., and K. G. Britton, B.A. (see vol. 78, page 461.)

† See *G.E.C. Journal*, 1936, vol. 7, p. 94.

equal to the ratio of electric to magnetic field strength; this follows from the well-known result that an electron in crossed electric and magnetic fields, of constant magnitudes E and H respectively, moves with a *mean* velocity E/H in a direction normal to both fields, independent of its energy. The time of precession between successive gaps in a cylindrical anode of radius r cm, with n pairs of segments, is thus approximately

$$\frac{\pi r}{n} \cdot \frac{rH}{KV} \text{ seconds,}$$

where KV/r is written for the electric field strength, K being a constant of proportionality. For resonance, in the sense used in the paper, this time must be equal to half the oscillation period, that is to $\lambda/(2c)$. Hence the optimum wavelength is

$$\lambda = \frac{2\pi c}{K} \cdot \frac{r^2}{n} \cdot \frac{H}{V}$$
$$= \text{constant} \times \left(\frac{r^2}{n} \cdot \frac{H}{V}\right)$$

which agrees with the experimental results. To obtain some idea of the value of the constant, we can put $K = 1$, which is at least a fair approximation to the truth when the anode current is limited by space charge. Then

$$\lambda = 4{\cdot}7\frac{d^2}{n} \cdot \frac{H}{V} \text{ metres}$$

where d is the anode diameter in cm, and H and V are measured in gauss and volts respectively. The quantitative agreement with the authors' empirical constant (approximately 4), and with the results of other investigators, is sufficiently close to suggest that what may be called the " precession theory " is on the right lines.

In the " resonant " condition, those electrons which are deflected outwards towards the anode each time they pass near one of the gaps also have to climb up a potential step in the neighbourhood of each gap, and so approach the anode with continually falling energy, eventually reaching it with a velocity which may be much less than $\sqrt{(2eV/m)}$. Other electrons, however, fall down a potential step in passing each gap and receive successive deflections which tend to return them to the neighbourhood of the cathode, where they may arrive with much more than their initial energy.

It seems possible, along these lines, to explain most of the observed characteristics of the split-anode magnetron at wavelengths of the order of 1 to 100 metres, including the peculiar capacitance changes reported by McPetrie,[*] and to give a simple physical interpretation to the ingenious but rather puzzling theory put forward by Posthumus.[†] I hope to publish a more detailed examination of these matters shortly.

The authors' statement on page 466 that " the ultra-short waves which this valve (a simple 2-segment magnetron) can produce are not of this resonance type " (i.e. the type discussed above) is misleading. The figures they quote refer to the " electronic " oscillations, which apparently involve a resonance with the electron rotation about the magnetic lines of force, but the published data for the valve in question include a Table (under the heading " Dynatron Oscillations ") showing that there is an optimum magnetic field strength for producing oscillations of a few metres wavelength which increases with both anode voltage and wavelength. In my opinion these latter oscillations are of precisely the same type as those discussed by the authors, although under practical operating conditions $nV\lambda/(d^2H)$ is not quite constant and is usually less than 4.

I do not agree with the authors' statement that space-charge effects are inoperative in the generation of negative-resistance oscillations. So far as the static characteristics are concerned, I have found that the negative-resistance characteristics occur only when the total anode current is space-charge limited, i.e. when it is less than the total filament emission. The authors' Fig. 5 is not inconsistent with this conclusion. It must be remembered that space-charge limitation begins to occur as soon as H is large enough to cause an appreciable drop in anode current, however small the filament emission may be. It is more difficult to decide whether or not space-charge limitation is essential for the " resonance " negative-resistance oscillations, but it appears to play at least an important secondary part in their production.

Fig. 7 suggests that the static negative-resistance characteristics disappear when the magnetic field strength exceeds about twice the critical value. In general, however, these characteristics extend to at least 8 times the critical field strength, but the negative slope is always greatest when the field just exceeds the critical value. The authors' result is doubtless due to the small emission current used. For the efficient production of long-wave oscillations, both emission and field strength must be rather large.

Can the authors explain the fact that the " cut-off characteristics " shown in Figs. 3 and 4 approach the theoretical ideal more nearly as voltage and field strength are reduced, while their comments on page 462 would lead one to expect the opposite?

Messrs. E. W. B. Gill and **K. G. Britton** (*in reply*): We especially mention in the paper that, in order to ascertain what is happening in a magnetron, it is essential to keep the filament emission and the resulting oscillations as small as possible; the results for maximum high-frequency current were obtained under these conditions. Messrs. Awender and Tombs do not state whether the same conditions were obeyed in their experiments. If the voltage-swing of the oscillations is at all large it would be extremely difficult to calculate the best working-point, and we should certainly not expect our last statement on page 463 to hold true.

With regard to the last paragraph in Messrs. Awender and Tombs's communication, stating that they have obtained shorter wavelengths than we have with a CW 10 valve of the same dimensions as ours, we have found that valves apparently similar show wavelength variation. The wavelengths depend on the distance between the filament and the gaps (or the nearest gap if the filament is not quite central). The anode diameter is only 5 mm, so that quite a small displacement of the filament from the central position produces a large percentage variation.

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[*] *Nature*, 1936, vol. 137, p. 321.

[†] *Wireless Engineer*, 1935, vol. 12, p. 126.

With reference to the second paragraph in Mr. Megaw's communication, the work done by the electric field on an electron with charge e moving from a filament at zero potential to an anode at potential V is in general eV, and is quite unaffected by any magnetic fields it has passed through. The only case where it differs from eV is when V is varying so rapidly that it changes appreciably during the time of a direct transit. For ultra-short waves this does, as in the Barkhausen oscillations, result in electrons arriving with less than the velocity expected from the instantaneous value and assists the regeneration; but for the longer waves we used the effect would be small and of only secondary importance.

We are much indebted to Mr. Megaw and interested in his calculations of optimum wavelength.

With regard to our statement on page 466 concerning ultra-short waves, we should like to summarize the results of our printed paper, and of one now in preparation. There appear to be three possible types of oscillation with a magnetron:—

(1) The dynatron type described on page 463.

(2) The resonance type described on page 466, in which an electron receives successive impulses as it passes *each gap in turn*, which impulses combine if applied at the proper frequency, to take it to the anode at the lower potential.

(3) Another resonance type in which the electron receives two or three impulses when passing near the *same* gap. This results in the production of ultra-short waves, i.e. waves which for a given V and H are shorter than those of type (2). This last type is the subject of the paper in preparation.

We regret to find ourselves in complete disagreement with Mr. Megaw's comments on space-charge effects. His extreme statement that "space-charge limitation begins to occur as soon as H is large enough to cause an appreciable drop in anode current, however small the filament emission may be" seems to indicate a complete misapprehension of space-charge effects. To put it as simply and briefly as possible, space-charge limitation in any electrical discharge is due to an electron, which is moving slowly, finding itself in a region where the electric field, due to all the electrons between the electrodes, is more than sufficient to counterbalance the electric field due to the potentials applied to the electrodes, and causes a reversal of the electric force in the region.

The limitation or decrease of anode current in a magnetron when the magnetic field is increased is due solely to the magnetic field conducting some of the electrons back to the filament and requires no reversal anywhere of electric field.

The only place in a magnetron where the space-charges can produce any effect is in the neighbourhood of the filament, for at all other places their velocity is considerable. If there were no magnetic field and, say, 200 volts on the anode, the maximum current that would pass across the valve would be well over 100 mA, and this represents the current required to give sufficient space charge near the filament to cause a neutralization or reversal of the electric force there due to the 200 volts. The application of a magnetic field does not sensibly alter this figure directly. What it does, however, when oscillations of the type we have investigated are occurring, is to cause the electrons continually to pass close to the filament and thus increase the space charge there. With an emission of 1 mA the electrons would each have to describe at least 100 orbits before space-charge saturation at the filament was reached. We have recently found that emissions of 0·01 mA will produce oscillations, which would involve 10 000 orbits being described before they reached an anode if the effect were due to space-charge limitation. It is obvious that this is impossible. It is not denied that as the filament emission is increased a point will be reached where space-charges begin to have some effect; but under the conditions of our experiments they were inoperative.

With regard to the last paragraph of Mr. Megaw's communication, we cannot give the explanation asked, but experiments with various valves show that slight irregularities in construction and very small tilts of the magnetic field from absolute parallelism with the filament cause surprising variations in the shape of cut-off curves.

DISCUSSION ON
"NOMOGRAMS IN ELECTRICAL ENGINEERING"*

Mr. H. J. Allcock (*communicated*): The author condemns the use of determinants as the basis of the nomogram on the ground that many electrical engineers have no knowledge of them. This will hardly be generally agreed, however, when it is remembered that electrical engineering problems involving network equations are commonly solved by the aid of the more elementary properties of determinants. It is only the most simple and elementary properties of determinants which are employed in the practical design and construction of nomograms; and, in any event, the requisite knowledge could readily be obtained from any standard textbook of algebra. It is perhaps not so much the mere use of determinants as their use in conjunction with the system of parallel co-ordinates which has rendered the theory obscure in the past. In the more modern treatment of the subject, however, consistent use of Cartesian co-ordinates in conjunction with determinants has enabled the theoretical treatment to be presented with greater clarity and the practical work of construction to be much simplified.

It appears from a study of the paper that in one case at least (i.e. the nomogram on page 576 for the formula $a - b + b^2c = 0$), the construction of the nomogram has been simplified by means of a mathematical operation which is at least of as advanced a nature as the properties of determinants mentioned above. In the more complicated forms of nomogram, mathematical operations of a still more advanced character would be required if simplicity of construction were desired. A knowledge of advanced mathematics is not, however, required if the nomographic theory is based upon the use of determinants. In cases where two or more of the loci are curved, the use of determinants affords the only practical method of design and construction.

The geometric method which the author puts forward has the advantage of simplicity in the majority of examples given. It lacks, however, the virtue of being generally applicable to all classes of formulæ, so that in many cases an easy geometric solution is either impossible or requires considerable ingenuity, and the nomogram may be laborious to construct.

It is also to be observed that it is sometimes desirable to alter the relative disposition of the loci in a nomogram. This transformation may be carried out graphically, but this necessitates great care both in the construction of the original nomogram and in the operation of transformation, and the chances of ultimate error may be relatively large. When determinants are employed, however, the necessary transformation may be carried out mathematically before any attempt is made actually to construct the nomogram, and the possibility of error in the final result is negligible.

Again, in all the examples given in the paper, the same scale (in the engineering-drawing sense) has been used for all the loci forming the nomogram. This is frequently not desirable from a practical point of view. The geometric method, where differing scale factors are employed for the various loci, would appear to be somewhat laborious except in the simplest cases. The standard forms of determinants for all nomograms consisting of three loci have been worked out and tabulated, together with the constructional determinants containing scale factors. Once, therefore, such a formula has been expressed in determinant form, the constructional determinant may be written at once in its correct form and, after making simple calculations for appropriate scale factors, the nomogram can be drawn.

For a proper appreciation of the theory upon which the construction of nomograms is based, it is only necessary to be able:

(1) To write any given formula in the form of a determinant, and

(2) To apply the following elementary properties of determinants equal to zero, namely that

  (i) Rows may be changed into columns, and columns into rows.
  (ii) Any two rows, or any two columns, may be interchanged.
  (iii) The elements of any row, or of any column, may be multiplied by the same quantity, or divided by the same quantity.
  (iv) To the elements of any row, or column, may be added the corresponding elements of any one or more other rows, or columns.
  (v) To the elements of any row, or column, may be added the same multiples of the corresponding elements of any one or more other rows, or columns.

In view of the simple nature of the above mathematical operations, it is suggested that a geometric method of design and construction offers no real advantages over the now well-known method based on the use of determinants in conjunction with Cartesian co-ordinates, particularly as the latter method has certain practical (as well as theoretical) advantages, which are not otherwise obtained.

Dr. E. A. Hanney (*communicated*): The paper anticipates one which I have been preparing. It is a matter for some disappointment that the author has covered so much of the ordinary textbook ground. One is bound to agree with him that the use of determinants as a basis for nomography is calculated to discourage the potential user; but, of five textbooks* which I know, in English, only one makes use of determinants, and the others appear to have been written with the same objects in view as those of Prof. Kapp.

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* Paper by Prof. R. O. Kapp (see vol. 78, p. 567).

The importance of *functional* scales (where graduations are spaced out according to values of some function of a variable, whilst they are labelled with values of the variable) is pointed out by Prof. Kapp. Whilst every engineer may know that powers, roots, logarithms, sines, cosines, hyperbolic sines and cosines, etc., are functions, it is important for him to realize that not all functions are mathematical. An engineer's data curves may be empirical or experimental, and may still show values of a function (an example occurs in the magnetization curve of an electrical machine, where the flux is a non-mathematical function of the field m.m.f.). Many useful nomograms can be made to record empirical data; thus I make use, in classes on the design of electrical machines, of a chart for each class of machine, showing the relation between d, l, and the approximate kW/r.p.m. Emphasis is laid on this because writers seem invariably to choose examples which use mathematical functions.

In my opinion the type of relationship which most commonly lends itself to representation by means of a nomogram is $f_1(x) \times f_2(y) = f_3(z)$, where $f_1(x)$ is "some function of x," etc. Writing this as $ab = c$, it is clear that charts with three parallel straight lines and logarithmic scales, or, alternatively, charts with two parallel lines and a slanting line, may be constructed; or, again, a chart with three straight lines through a point may be used to represent this same relationship, since one may take logarithms of the functional values and then plot scales according to the reciprocals of the logarithms. Furthermore, in each of these types, any one of the three variables—x, y, and z—may be arranged along any axis. Thus there are 9 possible arrangements; and in each arrangement there are unlimited possibilities in the spacing of lines. Naturally, the scales of such nomograms, if plotted to represent a simple relation $ab = c$, would vary greatly from one type to another. This property is very useful when plotting functional scales, since such scales may show very uneven divisions in one chart, and much more even divisions in another arrangement. My practice is to sketch many possible arrangements before making a decision.

A device for varying the spacing in the divisions of a scale, of which I have seen no mention elsewhere, may be adopted in the Zed chart (chart with a sloping line), but not in any other type. This is merely involution; thus if $a/b = c$ is charted, and two even scales are obtained for a and b along the parallel axes, the relation $a^n/b^n = c^n$ may be charted with uneven scales for a and b. An example is given in Fig. A. This useful chart, for obtaining K_g, the air-gap coefficient of a machine, replaces a formula containing a Carter coefficient which is read off from a curve. In the simple form, the nomogram exhibited on the right hand a functional scale which closed up badly towards the top, whilst that on the left hand was even. By taking square roots throughout, the right-hand scale was improved without spoiling the left-hand scale unduly.

Prof. Kapp refers to the "charts with a curved line," in which the equation represented contains two different functions of one variable. Now it is worth knowing that the relation between these two functions need not be a mathematical one. Fig. B is an example of a chart which deals with a magnetic calculation, and contains such a curved line. It shows the ampere-turns needed per cm on the teeth of a machine, when slots form parallel flux paths, and the apparent density (assuming all flux in the iron and none in the slot) is easily calculated. (The iron for which the chart was drawn has characteristics found by taking K_s as unity.)

Examples may occur when it is felt that such a relation as $f_1(x) \times f_2(y) = f_3(z)$ is involved, but the nature of the functions is unknown. If particular solutions are known, it is possible to integrate the scales by careful drawing and continual cross-reference. Fig. C is an example of such construction, and again it is a chart useful to the designer of electrical machines. In this case the average ampere-turns per cm in a tooth can be read off, knowing the degree of taper and the density at the wide end. (This chart may prove useful to some in connection with induction motors. The iron for which the chart was constructed has characteristics found by taking the degree of taper as unity. It is the same iron as that for which Fig. B was drawn.)

The purely practical question as to when to attempt a nomogram may be simply stated in the following words: "Whenever data curves have two axes and a *family* of curves, it *may* be possible to make a nomogram having three lines, and such a chart can be read with greater ease and accuracy; whenever four variables occur in the data, simple nomograms may still be possible (as in Figs. 4, 10, and 11 of Prof. Kapp's paper)." The electrical engineer must not expect to be able to put in nomogram form *all* his data curves, and intelligent understanding is necessary in order to avoid waste of effort.

Dr. A. L. Higgins (*communicated*): The impression that remains after reading the paper is that an article of considerable length has been abruptly curtailed on the last page. Wherefore it is a bold statement to say that the paper affords knowledge sufficiently comprehensive to enable the reader to make for himself the majority of charts he will ever have occasion to use. The scope of electrical formulæ must therefore be very limited or the occasions will not arise. After 25 years' interest in the subject I still find difficulty with apparently simple forms.

The first three pages of the paper deal with the type of the general form of alignment chart in which the pivotal axis is central, and the cases in which the outer scales are equal merely follows from the fact that a and b are unity in the more general form of linear equation $ax + by = c$. An inherent defect of the paper is that this more general form is not fundamental, for then the important matter of scales would be introduced and also their effect upon the disposition of the pivotal axis, which incidentally is not always a central axis.

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* (1) "The Nomogram," by Allcock and Jones [Pitman]; this deals with determinants and classifies the formulæ which can be represented. (2) "Line Charts for Engineers," by W. N. Rose [Chapman and Hall]. (3) "Alignment Charts for Engineers and Students," by Kearton and Wood [Charles Griffin and Co.]. (4) "Nomography," by Brodetsky [Bell]. (5) "Graphical and Mechanical Computation," by Lipka [Wiley and Co. (Chapman and Hall)]. All these works owe a debt to "Traité de Nomographie" by d'Ocagne, and it must be acknowledged that the art of nomography is a product of French mathematical genius.

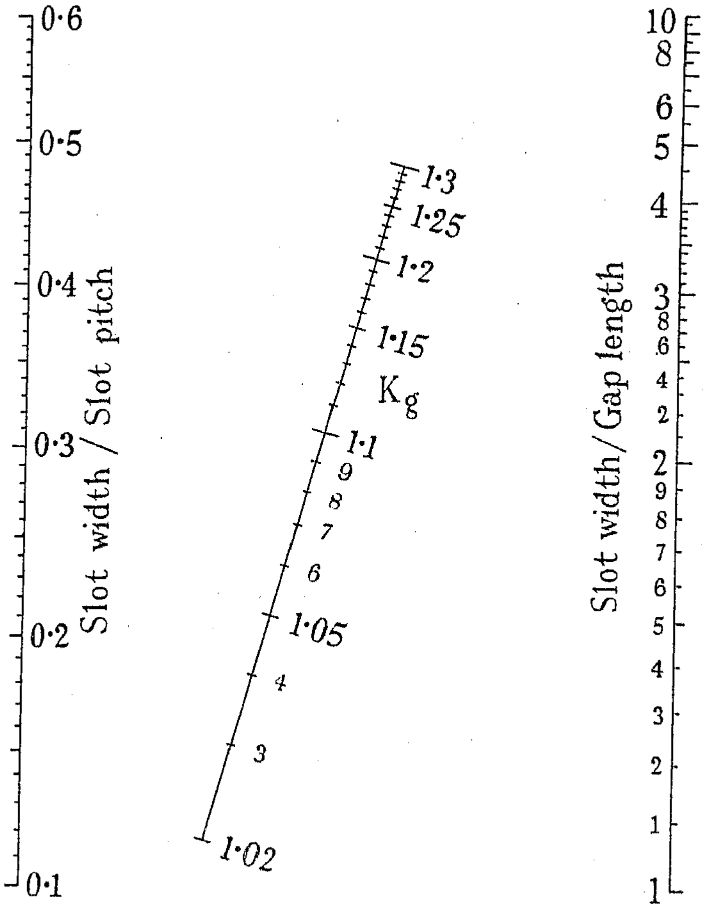


Fig. A.—Nomogram for air-gap coefficient K_g.

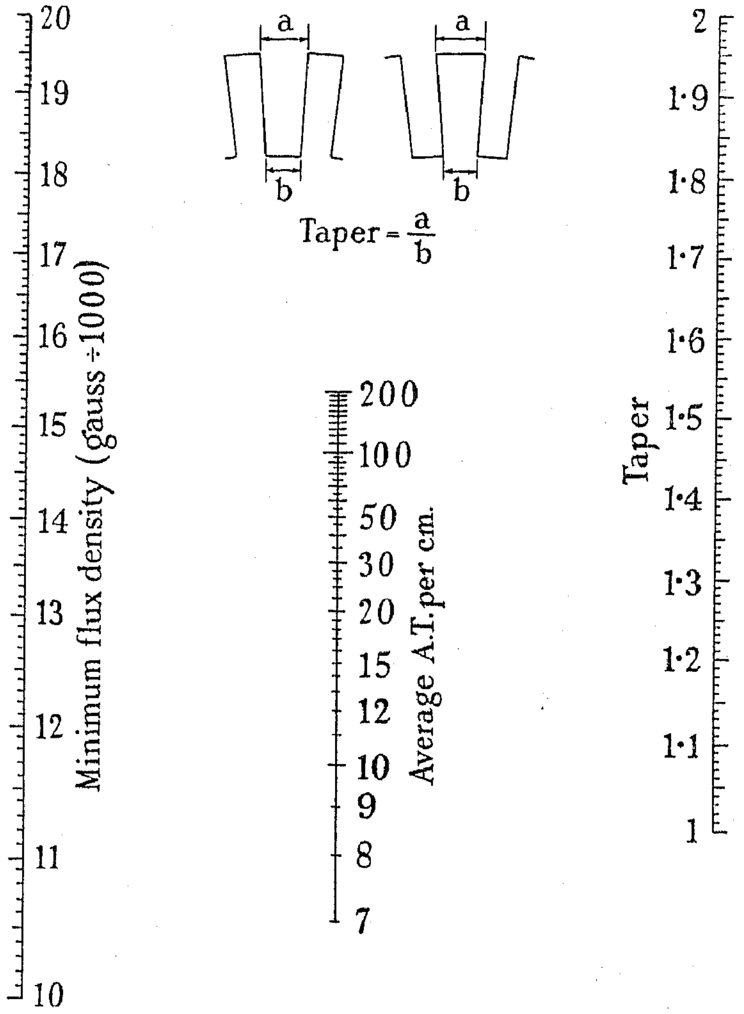
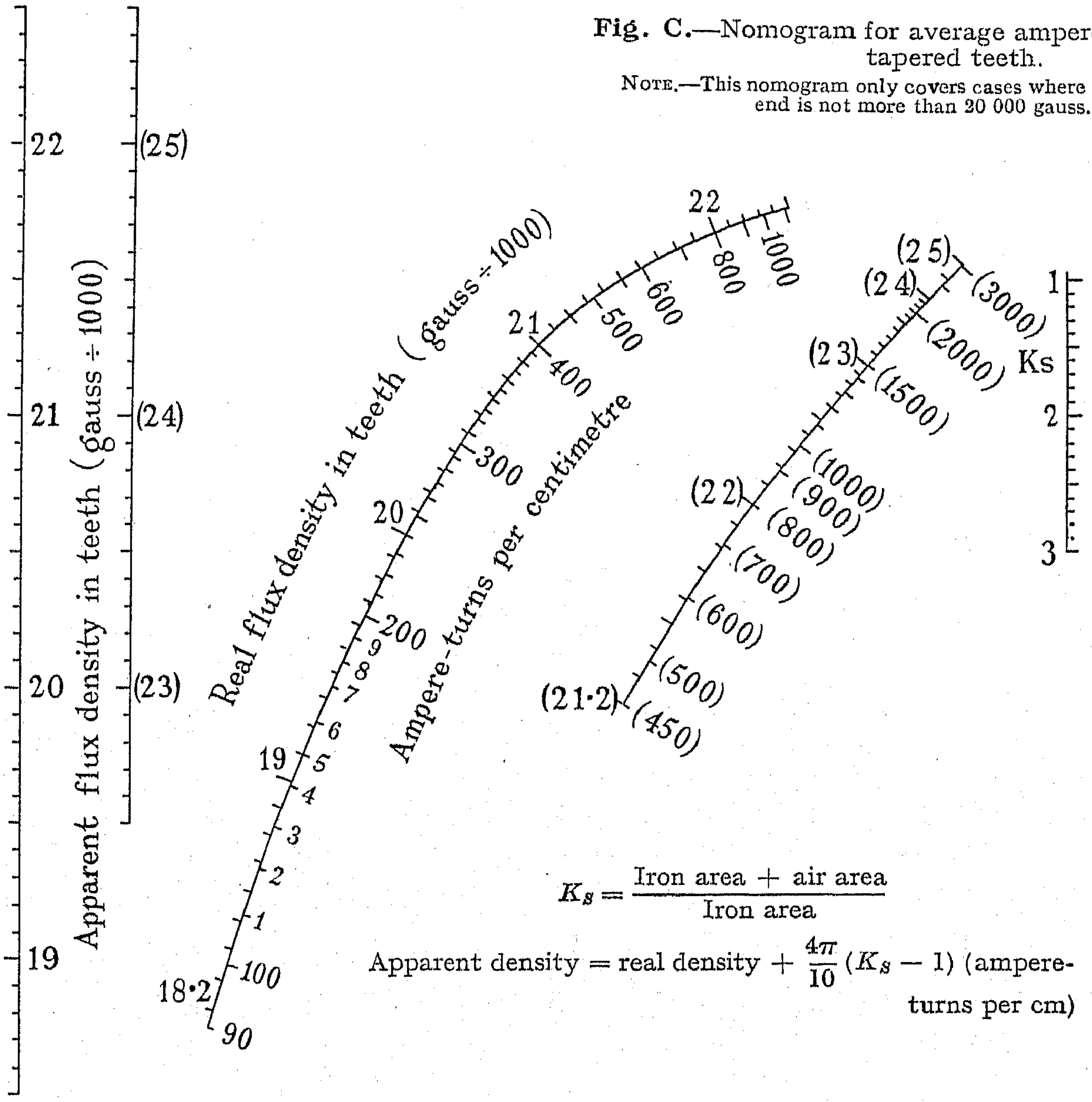


Fig. C.—Nomogram for average ampere-turns per cm in tapered teeth.

NOTE.—This nomogram only covers cases where flux density at narrow end is not more than 20 000 gauss.



$$K_s = \frac{\text{Iron area} + \text{air area}}{\text{Iron area}}$$

Apparent density = real density + $\frac{4\pi}{10}(K_s - 1)$ (ampere-turns per cm)

Fig. B.—Nomogram for actual density in teeth.

The author suggests the convenience of the scales of a slide rule, but says nothing as to how with little knowledge it is possible by cross-intersections to improvise charts *mechanically*. Associated with this mode of construction there are two little-known uses:—(1) Transformation of isoplethic diagrams to alignment charts, frequently leading to far more convenient forms. (2) Determining coefficients from experimental data, though the usefulness of the practice is not now considerable, since logarithmic paper is easily obtainable. All the same it is surprising how rapidly trial values can be obtained by ruling parallel scales, and thence by cross-intersections determining the appropriate values. Among examples that may be cited are:—Calibration of Venturi meters, tests on combined tension and bending, and determination of coefficients of viscosity.

The example of four variables in Fig. 4 does not cover the general case of four or more variables.

The charts with the pair of parallel scales and a diagonal are very well outlined, but only a small idea of the scope of this form is given. It is particularly applicable to exponential formulæ, such as $y = a^x$ or $T_1/T_0 = e^{\mu\theta}$.

Much might be written on the use of parallel scales and curves, as, for example, d'Ocagne's construction, introducing the hyperbola to the solution of quadratics, a process which can be extended to equations generally, as, for instance, the cubic involving the sag, tension, and loading, in overhead transmission lines.

It would be a courageous effort to attempt to treat so vast a subject from the engineering standpoint in a short series of articles, let alone in a short paper: nevertheless, on the principles which the author has enunciated, it is possible with perseverance to construct a considerable number of nomograms of real practical value. On the other hand, much time may be spent fruitlessly unless the enthusiast has a sure foundation on the mathematical fundamentals of the constructions.

Prof. R. O. Kapp (*in reply*): Mr. Allcock makes out an excellent case for tackling nomography with the help of determinants rather than by geometry, and his valuable contributions to the subject could hardly have been based on any other method of approach.

There is no doubt that determinants are the proper scientific basis and that they are essential for a deeper study of nomography; the only question is whether they provide the most suitable door through which a novice whose mathematics are somewhat limited is to reach an understanding of the subject. Perhaps it is a matter of temperament. Personally, I find elementary and even moderately complicated nomograms easier to understand and explain in terms of geometry, but some engineers may find the approach by determinants a simpler one.

Dr. Hanney's comments are all the more welcome because he emphasizes aspects of the subject not often met with. Extension of the art of nomography to the representation of unusual types of formulæ is fascinating, but of less practical importance than the developments referred to by Dr. Hanney, which are directed to finding the type of chart that will give the most convenient scale divisions. The use of nomograms for functions which cannot be expressed in algebraic form, as pointed out by Dr. Hanney, is a field of considerable practical importance, and one which has been sadly neglected hitherto. It must, however, be remembered that curves tell one at a glance things about a function which nomograms conceal.

The paper had to be curtailed somewhere. The additions suggested by Dr. Higgins, and a great deal more, might have been included, and yet a reader familiar with the subject could well have regretted that the paper was curtailed where it was. A single paper on nomography must necessarily be but an introduction to the subject. If it covered too much ground and if it attempted to delve deeply into mathematical generalizations, it would be too theoretical to be of much use to electrical engineers. That generalization which connects the scales with the position of the intermediate (Dr. Higgins says pivotal) axis has, however, not been omitted. The connection, which Dr. Higgins appears to have overlooked, is made clear in Fig. 12 for the general form of linear equation. The most general form of linear equation (which incidentally contains two constants and not three) can be represented in one of two ways. One could either place the intermediate axis centrally and arrange the scales to suit, or first choose convenient scales and then arrange the intermediate axis to suit, so Dr. Higgins is right in saying that the intermediate axis is not always a central one. It must, however, be remembered that it always can be a central one. Three-variable formulæ are rare, of which the most practical representation is not such as to make the intermediate axis central.

DISCUSSION ON
"MODERN DEVELOPMENTS IN RAILWAY SIGNALLING"*

NORTH-EASTERN CENTRE, AT NEWCASTLE, 9TH DECEMBER, 1935

Mr. L. Ballan: I welcome the progress in signalling made in recent years, which has resulted in economy and improved traffic facilities. I hope that as time goes on the cost of modernized signalling systems will be so much reduced as to make it unnecessary to employ such things as ground frames worked by the trainmen, in order to keep down costs. Automatic and mechanically-worked colour light signals are a great help towards speedy and safe working even in fog, and make fog signalmen unnecessary.

Signal engineers should not overlook the need for improving manual mechanism, much of which is still too heavy to work comfortably. The author has referred to the desirability of all freight trains being braked; but until a really satisfactory automatic coupling, dispensing with separate brake and heater pipes, can be adopted as standard, the short runs of trains in this country between marshalling yards will retard progress towards universal braked working. The marshalling of the type of braked stock in use at present is too slow.

In order to ensure proper watching of trains on long stretches of automatically-signalled line, it might be possible to make use of a development of television, and arrange for pictures of the trains as they passed selected intermediate points to appear in the signal-boxes.

Mr. J. T. Thompson: I would point out that Fig. 25 represents the layout of the new inward goods yard at Hull, and that the control tower is situated just below the bottom brake at the position marked "A1." The control of both the brakes and the power-operated switches is effected from this tower, from which an excellent view of the whole of the yard is obtained. This is only the second yard in the country at which the Fröhlich type of rail brake has been installed.

Mr. E. G. Brentnall: Axle-counter systems (page 357) seem to open a field where the installation of track circuits would be difficult owing to the presence of a considerable amount of coal-dust or sand, but, owing to the necessity for the provision of a treadle at every point of entry to or exit from the area, and to the number of line wires required, such counter systems appear to be too expensive for use in any but exceptional circumstances at present.

On page 370 the author refers to the use of petrol-engined alternators as standby sets; similar sets in use in the North-Eastern Area of the L.N.E.R. are started automatically and take the load in considerably less than ½ minute. I am in agreement with the author regarding the necessity for frequent test-running of the standby sets. Those just mentioned are run every Saturday morning.

With reference to secondary batteries floated across rectifiers at track-circuit locations, since the load is sensibly constant, in effect the rectifier provides the supply, the battery only coming into use on failure of the power supply. Has the author experienced any case where the battery has deteriorated under such conditions because it has not been subjected to a measure of charging and discharging?

With regard to code control of points and signals, owing to the conditions in this country it would appear that the use of each wire for several functions, with no coding, will be the line of earliest development here.

Mr. G. C. Thew: Dealing with the question of education, it appears to some extent necessary to educate also men other than the signal maintainers. Slight troubles have occurred at times when platelayers have put uninsulated gauges across the track or pushed bogies laden with materials into sidings, part of which have been track-circuited. In the latter cases, the track circuiting has probably resulted in the clearance points between tracks being revised.

The question of power supplies is one that has caused considerable concern. Absolute reliability of the supply is essential, and it is preferable to obtain two independent sources of supply. Previous to the grid's coming into being, this condition could be fulfilled. I have in mind a case where the supply authority had given what practically amounted to a guarantee of a continuous supply, but after they had become linked to the grid they withdrew their former undertaking. The load factor of a signalling installation is probably over 95 per cent, and this in itself should make a great appeal to the supply authorities, as I think it is higher than most other commercial consumers can give.

The paper rather gives one the impression that all signalling systems are complicated. This is not the case; a great deal is still being done on the mechanical side. The increased distances over which mechanical working of points has become possible are largely due to the introduction of track circuiting. Further investigation with the object of easing the manual work of the signalman where the points are a long distance away is, I think, required. The present normal limit for mechanical working is 350 yards, but there are many instances where this distance is exceeded. A great deal of work has been done recently in the way of adding electrical controls and interlocking to the existing mechanical systems.

[The remainder of Mr. Thew's contribution was similar to his remarks in the Leeds discussion (see vol. 78, page 378).]

Mr. S. A. Simon: My company recently adopted track signalling to protect several level crossings of their colliery railway sidings. On the approach of a train from either direction red lights show down the roads, and green lights show on the railway to indicate to the driver that all the red lights are in order; the lights are extinguished as soon as the last wagon of the train has cleared the road. On one of the roads (the main turnpike) at first the red lights did not go out when the train cleared the road, but only after the train had left the track-circuited system. The nature of the road material was suspected—as it appeared to be of very low resistance—and eventually we took out the macadam along one of the track rails and substituted creosoted wood in order to insulate it.

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* Paper by Major L. H. PETER (see vol. 78, page 353).

Another trouble is the very rapid wear of the insulation at the rail joints between the sections of the track: this requires renewing about every 6 weeks, which makes the cost of maintenance very high.

If these troubles could be remedied there would no doubt be ample scope for the application of track signalling to level crossings in colliery districts, so as to save the wages of flagmen. I should like to know what could be done to simplify and improve the apparatus, so as to reduce the maintenance cost.

Further information on the nature and qualities of road material at level crossings and their effect on the signalling system is also desirable.

[**Mr. A. E. Tattersall** also took part in the discussion. The substance of his remarks will be found in the report of the Leeds discussion (see page vol. 78, 376).]

Major L. H. Peter (*in reply*): Mr. Ballan's remarks are welcomed as showing that the developments in modern signalling are appreciated. The manual mechanisms as distinct from the power mechanisms referred to in the paper have also undergone considerable development and improvement in the period under review. The use of television, particularly for watching the approach to level-crossings, has been suggested on several occasions, but the cost of satisfactory apparatus at present makes the proposition non-economic.

I thank Mr. Thompson for giving the additional information necessary for Fig. 25.

With regard to Mr. Brentnall's remarks, it is made clear that the axle-counter system is considered to be one for use under special conditions and not as a general substitute for the track circuit-system.

The use of secondary batteries floating on rectifiers is very wide, and the question of deterioration receives much attention. Provided that cells of a suitable capacity, having a Planté-formed plate, are used and overcharging is not carried to excess, very little trouble is experienced from deterioration.

Referring to Mr. Thew's remarks, I agree that other departments have to be educated on matters which are of mutual interest, and in particular those whose work necessitates their dealing with portions of the track circuits and points.

Probably the best method of getting successful co-operation is by a series of well-illustrated lectures attended by both departments and providing as much discussion as possible.

I agree that continued development takes place in the mechanical portion of points and signals and that a judicious use of lock-detection and other appliances in conjunction with the mechanical systems will, however, help the development of the latter.

Mr. Simons refers to the rapid wear of insulations of rail joints and the consequent high maintenance cost. Failure of insulations of this nature is generally due to the joints being loose or to badly-packed sleepers. If the road bed is kept in good condition and the joints rigid, very little wear of the insulations takes place.

SCOTTISH CENTRE, AT EDINBURGH, 25TH FEBRUARY, 1936

Mr. A. Moss: Up to about 10 years ago railway signalling in Scotland was not very progressive, but happily these conditions have since been changed. We can now boast of having representative examples of most of the apparatus described in the paper, with the exception of automatic train control, centralized train control, and mechanized hump yards.

The subject of automatic train control is exercising the minds of all the railway companies very largely at the present time. Great Britain is now very much behind other countries in regard to automatic train control, for in America, Germany, and Italy, it has been developed to a very large extent. Undoubtedly the ideal method of train control is to repeat permanently in the cabin of the locomotive an indication of the signal which is being approached. This necessitates the continuous circuit-code system which the author has described. The cost of such a system can, however, become so high as to make its use on a large scale practically prohibitive, and therefore an alternative system has been adopted in the form of the intermittent inductive system, or contact system, described in the paper. Is the coder which is in use in the United States a fairly reliable piece of apparatus under all the varying railway conditions? In this country there is a school of thought which is rather opposed to any signal indication being given in the cab of the locomotive, primarily on account of the possibility of its distracting the attention of the driver from the line. What are the author's views on this aspect of the subject?

In regard to power supply and distribution in relation to railway signalling, development is being hindered because the cost of getting a supply of current generally is too high. The use of paper-insulated, lead-covered cables is now being adopted, and I think it is quite a successful procedure provided the cables are installed with due care. The method of using single wires, too, has certain merits, and I think a combination of the two is perhaps the best.

The signalling engineer's job is not finished with the installation of the plant: efficient maintenance of the plant is of the utmost importance, and this necessitates the training of men to take over the care of the apparatus after it has been installed. Some of the railway companies have signalling schools at certain centres, and others employ mobile instruction cars, equipped with apparatus, which are sent about the country to various depots. Another method of training is by means of correspondence classes, and the principle of giving a "refresher" course to linemen is also adopted by many administrations.

The practice of recording failures is a most important one. In London, where there is a large population and dense suburban traffic, any interruption of the train services reacts very seriously on the working of the transport system, and therefore some method of recording failures and following these up to the source is essential.

Mr. D. Mitchell: We are experimenting on the L.M.S. Railway with an installation of automatic train control which is operated by a system of permanent magnets and electromagnets situated between the running lines.

I should be glad if the author could tell us something about relay interlocking apart from the C.T.C. system. There seems to be great scope for that type of interlocking where signals are operated from thumb switches and the points operated by mechanical levers.

Mr. D. Old: Many American engineers spend a lot of money on modern signalling devices. I should like to know whether the author can state when it becomes economical to install C.T.C. signalling rather than the ordinary remote control system.

Mr. G. Henderson (Edinburgh): This past winter a great deal of time has been wasted on account of the delays due to fog on the railways in and around London. Much of this time would have been saved had some form of automatic train control such as the author describes in his paper been introduced.

On page 356 he makes reference to harmonics on the d.c. side of the system due to the supply from the rectifier, and the influence of the d.c. load on the waveform on the a.c. side. I should like to know whether the author analysed this a.c. supply wave, and, if so, what value of 6th harmonic he found. He states that the existence of this 300-cycle ripple caused interference with the signal system; I should be interested to know how this trouble was overcome, as I understand that the railway company in question have no series choke coil or filter circuit on their system. I should be glad if the author would confirm that when an overhead d.c. supply system is used the installation of a wave filter is unnecessary. As regards his statement that by using 12-phase rectifiers the harmonic value would be so reduced that there would not be any interference with signals, I doubt whether this would be found to be the case, because at light loads the rectifier no longer operates as a 12-phase rectifier but gives ripple values corresponding to a 6-phase rectifier.

Major L. H. Peter (*in reply*): Mr. Moss in his opening remarks refers to cab signalling. The cost of cab signalling, although it may appear high when first considered, would probably not appear in the same light if the cost of all those accidents which would have been prevented by cab signalling were taken as a standard of comparison. The coder referred to is a reliable piece of apparatus which I have no doubt will become regarded in the same light as our present-day track relays.

I do not agree that placing a cab signal in the locomotive will distract the attention of the driver from the line. In my opinion nothing but good can result from placing the signal, which gives a driver his instructions, in the place most easily visible to him.

Mr. Mitchell asks for information on relay interlockings, but relay interlocking is dealt with in the paper as part of any remote control system. For instance, in the C.T.C. systems referred to, code is only used for supervisory control and indication of a number of relay interlockings, code transmission being employed only between the thumb switches and the interlockings themselves.

In the case of the electro-mechanical system referred to, the combination pilot-switch control of signals and mechanical point operation is one sometimes adopted in modernizing older installations.

Mr. Old asks for a dividing line between coded remote control systems and wired systems. It is impossible to give any hard-and-fast division, as the number of indications to be conveyed and the relative costs of cable route have to be compared for each installation. In general, the greater the distance and the greater the number of indications to be transmitted, the greater is the likelihood that a coded system will be cheaper.

Mr. Henderson refers to the analysis of harmonics from the traction mercury-arc rectifiers, and methods adopted to overcome interference. To a large extent this question is dealt with by Mr. Challis's contribution to the London discussion.

I confirm that when an overhead d.c. supply system is used, filters would appear to be unnecessary as there is not a tendency for side current rails to cause the harmonic component to be carried by one rail only on the permanent way. It is a fact that the ripple current which is carried by one rail and consequently by one half of each impedance bond winding, leads to an unwanted voltage being applied to the track relays. In an overhead d.c. system there would be no current rail and it would be expected that the ripple current would be distributed fairly equally between the two running rails.

DISCUSSION ON
"ROUTINE OVER-VOLTAGE TESTING OF HIGH-VOLTAGE CABLES"*

NORTH MIDLAND CENTRE, AT LEEDS, 3RD MARCH, 1936

Mr. S. R. Siviour: The conditions with which the author has had to deal are somewhat abnormal in that he has been mainly concerned with cables manufactured and laid many years ago for much lower working voltages which were subsequently operated at 11 kV; the number of breakdowns therefore appears to be very high. This, however, does not detract, in my opinion, from the value of routine testing for eliminating weak spots in old cables. I mention old cables because I consider that, as a result of the extraordinary advance in cable technique which has been made during the past 5 to 10 years, the modern cable is so reliable that it is not necessary to subject it to routine tests.

I fully agree with the author that the use of high-voltage direct current is the only practicable method available for the field test. Provided the appropriate voltage is applied, no harm is done to the cable by such a test. A short-time test of 1 minute is all that is usually necessary; there is no advantage in applying a sustained over-voltage, as most cables break down under this test before reaching the maximum test voltage. The only exception to this rule is the case where, after the maximum voltage has been reached, the current fluctuates and an unstable state is indicated. This may be due to defective insulation at or near the breakdown stage, or possibly to leakage over terminal ends, particularly where outdoor insulators or damp substations are concerned. In such cases, the voltage should be maintained until failure occurs.

The d.c. stress when applied does not cause any additional movement of ions and, hence, plays no part in the process of breakdown in the tracking type of failure, with which we are mostly concerned. The tracking type of breakdown is a gradual process, and investigations into many faults lead me to the view that the last stage is comparatively rapid. If, therefore, a cable breakdown occurs in service shortly after a routine d.c. test, it merely indicates that at the time of the routine test the remaining wall of sound dielectric at that spot was sufficiently good to withstand the test voltage, but subsequently broke down in service under the devastating a.c. discharge.

I rather question the author's use of 50 kV, both between lines and to earth, but it may be that this was influenced by his desire to test his joints thoroughly. It is of interest to recall that on a total length of over 500 miles of 11-kV cable we had only 5 joint failures last year, and some of these were at terminal boxes of the outdoor type.

Mr. G. Ezard: I should like to refer to one or two tests which I have witnessed on 11 000-volt mains in this district.

(1) A service fault having occurred in June, 1934, the cable was subjected to a d.c. pressure test the following October. First of all, 35 kV was applied between each core and the earthed sheath; no breakdown occurred. Next 55 kV was applied between two cores at a time, and after $4\frac{3}{4}$ minutes failure occurred. I am unable to contribute to the view that a test time of 1 minute is sufficient, because here we have a concrete case of the voltage being sustained for $4\frac{3}{4}$ minutes before the incipient fault had been completely broken down. Subsequent examination of the fault showed definite signs of an incipient a.c. fault between two cores. There has been no further fault on this main.

(2) In the second case, on another main, a service fault also occurred in June, 1934, and a d.c. test was conducted the following November. The test at 35 kV between cores and sheath was satisfactory, but the cable failed when 20 kV was applied between two cores. Repairs were carried out, and on the following day the test was repeated without any failure. Within 17 days the cable failed during service.

I refer to these two examples because to me the problem of the time-interval between routine tests is difficult of solution. I believe the author tests at intervals not exceeding 6 months; it is certainly better to carry out these tests even every 6 months than to risk a service breakdown with its attendant complaints, but on cables which are particularly suspect the tests will have to be more frequent—at any rate until the more advanced incipient faults have been removed.

On page 84 of the paper I read that "Ingress of moisture . . . penetrates from without." Does this mean that all the moisture to be found in a faulty cable has gained ingress through a defective sheath? It has been my experience when dissecting faulty cables to find moisture present only in those papers immediately adjacent to the strands; as no trace of water is found in fillers or belt, this moisture must have entered at the ends of the cable.

The availability of cables for routine testing presents many operating difficulties, especially on radial feeders, but there must surely be some nights or week-ends in the year when arrangements can be made with consumers for the cables to be taken out of commission. The time required to carry out a test and repair a fault may well be illustrated by the following example. An 11-kV feeder 2 miles long and having only one source of supply was taken out of commission at Saturday midnight. By 12.22 a.m. both ends of the cable had been disconnected from the switchgear and the test leads fixed. At 12.48 a.m., after a series of "core to earth" tests, failure at 35 kV took place. The voltage had remained constant for 45 seconds. The location was carried out by means of a high-voltage bridge, and by 2.20 a.m. the labourers had excavated sufficient ground to enable a repair length of 20 yards to be inserted into the main. Two straight joints were made, and the main was recommissioned at 10.27 a.m. on Sunday. This d.c. test removed a fault at no inconvenience to consumers.

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* Paper by Mr. C. KIBBLEWHITE (see page 82).

Mr. A. C. Bailey: On page 82 the author mentions that in the first routine tests which were carried out he used a voltage of 50 kV between conductors and between conductors and earth. To my mind this was a mistake, as either the test voltage between the cores was too low or that to earth was too high.

Table 1 is not much of a guide. It refers to the cables of small dielectric thickness, and can therefore apply either to some of the earlier lower-voltage cables or to some of the more recent cables which it has been possible to make of smaller dielectric thickness owing to the present higher standard of the cable manufacturers' art.

On page 83 the author states that high-voltage d.c. tests cannot cause damage unless actual breakdown occurs. If this is so, there is no question that high-voltage d.c. testing is the correct thing; but it is my experience that such tests do cause damage. The mere fact of time being required to break down the cable shows that the test is having a damaging effect.

I would point out that joint-box failures to earth such as those mentioned in Table 2 can be expected if one is carrying out the same pressure test to earth as between cores, as the " between " test is then not such a severe test.

The question of the speed of deterioration of a faulty cable, mentioned on page 84, is most elusive. There was one case where we purposely punctured the sheath of a 3-core 11-kV cable and then immersed the damaged portion in a water tank. This cable subsequently stood up to a 3-phase 11-kV supply for about 3 months without breakdown, whereas on other occasions I have known a cable to be damaged by men on road repairs and the sheath only just punctured, and yet the main has failed a few weeks afterwards.

While I agree that d.c. over-voltage tests are useful for breaking down incipient faults, I would prefer the test voltage not to be more than, say, twice the peak value of the service condition. If this does not produce a breakdown, a power-factor test should be applied by, say, a Schering-bridge method. I can quite see there is no point in applying the Schering-bridge test before a pressure test, as a bad spot would give a high power factor. One might consequently consider this represented the average condition of the cable, whereas the trouble would in reality be concentrated. The examples given in the Appendix show that incipient faults were found with voltages much less than those the authors suggest should be used. This alone indicates that 50 kV is too high a test voltage for 11-kV cable.

Mr. R. M. Longman: I am especially interested in the arrangements necessary with respect to the cable terminations in switchgear. The ordinary trifurcating boxes and porcelain end-bells in open-type switchgear apparently offer no trouble, but with those terminating in compound-filled or oil-filled gear the position is not so easy. It would be interesting to learn the author's experience with this latter type of gear.

He does not appear to have mentioned " cheesing," surely an omission when dealing with the life of cables.

A certain technique is soon obtained when doing much d.c. testing. The tester can, chiefly by watching the milliammeter, rapidly form a good idea of the condition of the cable. If the cable is in fairly sound condition there is nothing to be gained by extending the duration of the test; on the other hand such extension does not harm it. In this respect d.c. testing is quite the reverse of a.c. testing, which inflicts a sort of hammer blow 50 times per second. I recently heard of a case where the d.c. test was extended from 15 minutes to 30 minutes, and finally to 2 hours, without a sign of breakdown. Tests such as those described in the paper would have been very helpful to those engineers who during the past 20 years have had to change over distribution systems from d.c. to a.c. supply.

As cables are now of much larger capacities and larger loading—larger conductors and higher voltages—it is of increasing importance to avoid faults developing; hence the necessity of routine testing to discover incipient weaknesses.

Mr. C. Kibblewhite (*in reply*): Mr. Siviour concludes that it is unnecessary to routine-test modern cables, that direct-current should be used, and that a short-time test only is necessary except where an unstable state is indicated. I agree with these conclusions, but I think his suggestion is more debatable that service faults following shortly after a test are caused by the effect of a.c. discharge on the remaining wall of sound dielectric which has recently withstood a test. In some cases, at least, I believe that such faults are precipitated by voltage surges, which may reach values exceeding the effective d.c. test voltage, particularly on cables connected to overhead lines.

The tests described by Mr. Ezard are interesting, and I particularly welcome the views which his experience in the field has enabled him to put forward. I agree that suspect cables should be tested at short intervals. In referring to moisture in cables, I had in mind moisture which had penetrated through the lead sheath, and I have not come across cases where water has percolated along the strand from the terminals of an e.h.t. cable. I can, however, well believe that this might happen if a really good seal is not effected at the end. On repeated load cycles a cable tends to breathe and moist air may be drawn in, even through a very small aperture, and may travel a considerable distance along the cable.

Mr. Bailey criticizes the decision to use 50 kV both for between phases and for phase-to-earth tests, and he also connects the large number of joint failures with this decision. I think he will find that this matter has been dealt with fairly fully in the paper, and he will notice that in making a final recommendation I have suggested a reduction to 35 kV in the phase-to-earth pressure. I do not, however, agree with him that twice the peak value of the service voltage is sufficient for 11-kV cables. Whilst a power-factor test may be useful as a guide to the general condition of cables, Mr. Bailey will appreciate that such a test is of no value for the purpose for which the tests described in the paper were devised, namely the detection of local weaknesses. Mr. Bailey will find that in my reply to Mr. Clark and to Mr. Nethersole and Dr. Dunsheath I have dealt with the points referred to in the second and third paragraphs of his remarks.

In reply to Mr. Longman, we have certainly had a good deal of difficulty with compound-filled or oil-filled switchgear, and I mentioned in the paper that the paper-board insulation, which is often used on this class of gear, seems somewhat susceptible to breakdown at high d.c. voltages. With reference to his inquiry about "cheesing," we have not found much "cheese" in cables which have been operated for most of their working life at 5·5 kV. Cables operated at 11 kV do, however, sometimes exhibit this feature and, although it is evidence of ionization, it need not necessarily be considered to be a danger signal unless accompanied by the formation of carbon, in the form of either spots or tracking.

SUSPENSION INSULATORS FOR E.H.T. TRANSMISSION LINES*

By I. S. SCOTT-MAXWELL, Graduate.

(ABSTRACT *of Paper read before the* SCOTTISH STUDENTS' SECTION, *at Glasgow* 18*th October*, 1934, *at Edinburgh* 23*rd October*, 1934 *and at Dundee* 25*th January*, 1935.)

GENERAL

Past experience of high-voltage transmission has shown that, in this country, dirt deposits on the insulator, due to atmospheric contamination and periods of fog, represent a problem of the utmost importance. Most interruptions to supply are caused by line faults, and the majority of these are due to flashovers during periods of fog.

The possibility of lightning faults must also be kept in mind, but, generally speaking, any protection against this form of trouble is usually obtained by the use of apparatus external to the insulator or by increasing the number of units per string.

The greatest amount of dirt collects on the under-surface, and, owing to the corrugations being underneath, the greater percentage of the surface area thus becomes contaminated. The original reason for this design was to obtain a maximum amount of surface which would be protected from the rain. Only recently has this practice been altered.

Test figures show that during fog the porcelain surface of the insulator becomes almost continuously conducting, the power factor rising above 0·99 and the impedance becoming practically a pure resistance. This is chiefly due to the moisture of the fog dissolving the soluble salts already on the surface.

The present type of anti-fog unit is essentially different in that it has a large leakage surface. This is obtained by expansion, either vertically or horizontally. The horizontal expansion gives a unit of increased diameter and is much to be preferred. This gives an open under-surface which is easy to clean and does not readily collect pockets of ionized air.

In the anti-fog unit the under-surface represents about two-thirds of the total leakage surface, and the presence of dirt increases the leakage current considerably. Large leakage path has, however, more effect on the impulse strength of the unit than on conditions of dirt deposit, and the complete stoppage of streamer development prior to flashover would result in a better industrial insulator.

Deposits of dirt collect underneath, and, contrary to past beliefs, when insulators are operated in dirty atmospheres rain is distinctly more of an advantage than a disadvantage, because it tends to wash off any dirt which is present. A striking proof of the beneficial effect of the rain can be found in the behaviour of tension strings in industrial areas. Tension strings are held in an almost horizontal position by the direct pull of the line, so that both sides of the unit are exposed to the rain, and such insulator strings have only been known to flash over owing to lightning strokes. As a result of this observation, a suggestion which was put forward some years ago is now being tried out. An inclined unit is used and two strings are suspended in the form of an inverted V from the tower arm, held apart at the bottom by a steel bar in compression. The unit has no corrugations and is mounted in such a way that the plane of the shed is practically vertical. This gives to the suspension string the better cleansing characteristics of the tension string.

FLASHOVER

Considering the reasons for flashovers, we have the following main causes:—

(1) Lightning.
    (*a*) Direct hit.
    (*b*) Indirect hit (induced charge).
(2) Fog, mist, and dirt deposit.

Dealing with (1)(*a*), lightning voltages may be of the order of 30 000 000 volts. The quantity of electricity involved in any discharge is small, but the discharge time is so short that the current may rise to 10 000 amps. or more, the rate of expenditure of energy being very high. It is doubtful whether complete protection against direct hits will ever be possible with such voltages as these.

With regard to (1)(*b*), the indirect effect, a high potential of one sign is built up and held stationary in one portion of the line, due to a charge of opposite sign on a nearby cloud. When the cloud discharges to earth or to another cloud the line charge is freed and travels along the line as a steep-fronted voltage wave. This surge may spill-over at the first insulator it comes to, but if this withstands the initial kick in all probability no flashover will occur because the surge wave is attenuated very quickly.

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* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

Turning to cause (2), namely fog, mist, and dirt deposit, under certain conditions corona and streamer discharge will begin to appear around the upper end of the pin and between the bottom edge of the cap and the porcelain. The size to which these streamers grow and the voltage at which they appear depend chiefly on:—

- (*a*) The state of the insulator with regard to cleanliness, moisture, etc.
- (*b*) The shape of the porcelain.
- (*c*) The pressure, temperature, and humidity, of the surrounding air.
- (*d*) The voltage applied to the strings.

These streamers occur at points of maximum stress, i.e. where the field lines of force converging from the cap to the pin pass from the edge of the cap through the air to the porcelain and from the porcelain through the air to the pin. Their effect is to create eddy currents of air due to ionic winds, when the surrounding air is comparatively still. Under fog conditions this will have the effect of circulating a maximum amount of dirt-laden moist air around the corrugations and will thus increase the deposit at the very time when it should be kept at a minimum. Under wind conditions also, soot and dirt will be caught underneath, in consequence of the physical shape of the unit. If there is any appreciable wind present, the effect of the ionic wind will probably be nullified. This increased dirt deposit in turn increases the leakage current, so that the streamers grow still further and eventually small quantities of highly ionized air are held in the pockets between the corrugations. Ions diffuse very much more slowly in moist air than they do in dry air, because particles of moisture condense around the ions and the extra weight considerably lowers the coefficient of diffusion. The streamers eventually jump across the bottom edges of the corrugations and thus completely bridge the unit, putting an increased stress on the remaining units so that they in turn are bridged, the final result being a cascading flashover. Only a part of this outline of events is based on experiment, the rest being more or less inference.

CLEANING OF INSULATORS

All insulators have to be cleaned at some time or other, and in a transmission system the line insulators are cleaned most frequently. The cost of this cleaning is a matter of considerable importance and ought to be well considered during the designing of any particular unit. At present the cleaning frequency varies from about six times per year on dirty lines to about once per year on clean lines. It is quite reasonable to assume that even the best insulator will require a certain amount of cleaning. This should not be done more frequently than once every year for the dirtiest lines, and once every two years for the cleanest.

DEVELOPMENT OF THE IDEAL UNIT

The conditions which ought to be satisfied by any unit approaching the ideal may be summed up as follows:—

- (*a*) Long length of leakage path.
- (*b*) No corona formation until immediately before breakdown.
- (*c*) High ratio of impulse to normal voltage.
- (*d*) No tendency to be short-circuited by dirty-water drippings.
- (*e*) Ample mechanical strength.
- (*f*) Easy access for periodic cleaning.
- (*g*) Ease of manufacture.

Of all these conditions, the most important is (*b*). It has long been recognized that in order to prevent corona formation it is necessary to make the surface of the insulating material conform with the field lines of force between the cap and the pin. Little success seems to have been achieved in this direction. About the year 1922 the late Prof. H. B. Smith, of the Worcester Polytechnic Institute, U.S.A., made some experiments in an attempt to discover the ideal unit. He achieved remarkably good results, by making " the terminal flux distribution members," which were metallic, of such a shape that the field lines of force between these members were parallel to the surface of the insulating member. The unit flashed-over without any visible sign of previous corona, and would withstand a voltage greater than that of six standard 10-in. suspension units hung in parallel with it. The overall length of the suspension string was somewhat greater than that of Prof. Smith's unit. Developing this still further, he produced a unit whose insulating member was situated in a " hollow " field, i.e. a field more intense on the outside than on the inside. The result of this was that the flashover arc always struck between the end members; the insulating member, being at the centre of the field, was never harmed in any way.

Little reference can be found in published papers to field manipulation on suspension insulators for industrial areas. The hollow field design might be developed in the future so that dirt particles are actually prevented from coming into contact with the insulating material.

The future trend of investigation should be towards a unit which is easy to manufacture and will not show any signs of corona prior to breakdown. A long thin unit with the greater part of its leakage path exposed, and fitted with such arcing rings that the insulating material is placed in a hollow field, would constitute a big step towards the ideal unit for industrial areas. This would probably mean that the insulating material would have to be in tension, but it would seem a matter of much greater value to electrical transmission if an entirely new design was developed along these lines. The present type of " compression " insulator can never be a complete success in industrial areas, and will always involve a considerable amount of cleaning to ensure continuity of supply.

INSTITUTION NOTES

COUNCIL FOR THE YEAR 1936-1937

The scrutineers appointed at the Ordinary Meeting of the Institution held on the 23rd April, 1936, have reported to the President that the result of the ballot to fill the vacancies which will occur on the Council on the 30th September next is as follows:—

President: H. T. Young.
Vice-President: Johnstone Wright.
Hon. Treasurer: F. W. Crawter.
Ordinary Members of Council: (Members) T. Carter, C. E. Fairburn, M.A., F. Forrest, S. W. Melsom, P. J. Robinson, M.Eng.; (Associate Member) C. R. Westlake; (Associate) E. M. Lee.

The Council for the year 1936–1937 will therefore be constituted as follows:—

President.

H. T. Young.

The Past-Presidents.

Vice-Presidents.

A. P. M. Fleming, C.B.E., M.Sc.
W. E. Highfield.
Lieut.-Col. A. G. Lee, O.B.E., M.C.
Johnstone Wright.

Honorary Treasurer.

F. W. Crawter.

Ordinary Members of Council.

A. H. M. Arnold, D.Eng.
Sir Noel Ashbridge, B.Sc.(Eng.)
J. R. Beard, M.Sc.
E. S. Byng.
T. Carter.
C. E. Fairburn, M.A.
F. Forrest.
Prof. C. L. Fortescue, O.B.E., M.A.
P. Good.
E. M. Lee.
Brig.-Gen. R. F. Legge, C.B.E., D.S.O.
S. W. Melsom.
F. E. J. Ockenden.
P. J. Robinson, M.Eng.
J. W. Thomas, LL.B., B.Sc.Tech.
V. Watlington, M.B.E.
C. R. Westlake.
W. J. H. Wood.

Together with the Chairman of the Meter and Instrument Section, the Chairman of the Transmission Section, the Chairman of the Wireless Section, and the Chairman and immediate Past-Chairman of each Local Centre.

TRANSMISSION SECTION

The result of the ballot to fill the vacancies which will occur on the Committee of the above Section on the 30th September next is as follows:—

Chairman: Dr. P. Dunsheath, O.B.E., M.A.
Vice-Chairman: J. L. Eve.
Members of Committee: H. J. Allcock, M.Sc., H. W. Grimmitt, Major W. M. N. Morecombe, O.B.E., B.Sc. (Eng.), R.E. (Ret.), P. E. Rycroft, M.B.E.

CONVERSAZIONE OF OVERSEAS MEMBERS

A Conversazione of members from overseas and their ladies was held in the Institution building on Wednesday, 15th July, the attendance being about 130. The proceedings commenced with a reception by the President (Mr. J. M. Kennedy, O.B.E.). This was followed by short addresses delivered in the lecture theatre by the President on "The Organization of Manufacture, Development, and Research, in relation to the Electric Supply Industry," and by Dr. E. Mallett on "Television—an Outline." A reunion then took place in the library.

The following members from overseas were present: Mr. M. H. Advani (*India*), Mr. P. A. W. Anthony, B.E. (*Australia*), Mr. H. L. Barnard, B.E. (*Australia*), Mr. V. H. Bray (*Persia*), Mr. V. A. M. Bulow (*India*), Mr. C. Cater (*Brazil*), Mr. S. B. Deshpande, B.A. (*India*), Mr. H. J. Donkin, M.B.E. (*India*), Mr. G. Floyd (*India*), Mr. N. N. Ghose (*India*), Mr. L. B. S. Golds (*China*), Mr. E. J. B. Greenwood (*India*), Mr. E. P. Hambleton, B.E. (*New Zealand*), Mr. H. C. Hitchcock (New Zealand), Mr. M. J. Horgan (*South Africa*), Mr. P. S. E. Jackson (*India*), Mr. A. F. Johnston (*Italy*), Mr. J. P. Khanna (*India*), Mr. G. C. Kim (*Burma*), Mr. F. J. R. Mackenzie (*British Guiana*), Mr. E. C. Muir, B.Sc.(Eng.) (*China*). Mr. B. Price (*South Africa*), Mr. H. T. Priestley, B.E. (*Australia*), Mr. J. O. Renaut (*New Zealand*), Mr. C. G. Rudd, B.Sc. (*New Zealand*), Mr. G. N. Smith, B.Sc., (*Australia*), Mr. A. R. Tyrer (*Southern Rhodesia*), Mr. A. W. M. Watkins (*New Zealand*), Mr. K. E. Wilson (*Federated Malay States*), and Mr. M. Wilson, M.A. (*India*).

GRADUATESHIP EXAMINATION RESULTS: MAY, 1936

Passed*

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Andrews, William Thomas (*Edgbaston*).
Armstrong, Cecil James (*Cheadle Hulme*).
Ashby, Donald (*Shortlands*).
Ball, Ronald (*Coalville*).
Ballantine, David Russell (*Watford, Herts*).
Barber, Clyde Parsons (*London*).
Bardens, Arthur Thomas Bertram (*London*).
Beal, George (*Ashington, Northumberland*).
Bissmire, Henry George Thomas (*London*).
Brown, Frederick Oswald (*Edgbaston*).
Brown, Sidney Riley (*Acomb, York*).
Caister, Percy Richard (*Ashford, Kent*).
Clementson, John Salkeld (*Carlisle*).
Collins, Ivor Leslie (*Cardiff*).
Dunford, Leonard George (*London*).
Emerson, Alexander Hockley (*Peterborough*).
Evans, Thomas Fielding (*Cardiff*).
Fry, Maurice Frederick (*Bexleyheath*).

Passed—*continued*

Gaul, Richard John (*Loughborough*).
Hatt, George William (*London*).
Hemingway, Joseph Wilson (*Corstorphine*).
Hoare, Christopher (*London*).
Jackson, Gilbert (*London*).
Jarvis, Ronald (*Sandown*).
Jenkins, William Bingham (*London*).
Johnston, Wilfred (*Maltby*).
Kameen, Robert James (*Neston, Wirral*).
Linn, William Adam (*Cowdenbeath*).
Lomax, Geoffrey Raymond (*Dalbeattie*).
Lord, Cecil Grundy (*Timperley*).
McDermott, Owen Desmond (*Drumcondra*).
McKibbin, Edwin Lawson (*Douglas, Isle of Man*).
McLeod, John (*Edinburgh*).
Maurice, Richard Boyle (*Yeovil*).
Mukerji, Manik Lal (*Sheffield*).
Nicholas, Alfred James (*Sale*).
Ramsay, John Forrest (*Chelmsford*).
Reddy, Duvur Venkatrama (*Bishopstoke*).
Renton, Joseph Edward (*Blyth, Northumberland*).
Richards, Leslie Stephen (*Felixstowe*).
Richmond, Francis Arnold (*Newcastle-on-Tyne*).
Rushton, John Harold (*West Bridgford*).
Smith, Thomas (*Leicester*).
Smith, Victor Holloway (*Worksop*).
Thomas, Edward (*Rosyth*).
Timpson, John Graham (*London*).
Watson, Sylvester Neville (*Whitley Bay*).
Williams, William Lloyd (*Newport, Mon.*).

Passed Part I only

Brassington, Arthur Gerald (*Edinburgh*).
Evans, Herbert Martin (*Felixstowe*).
Hammond, Harold Frank (*London*).
Houston, David (*Haywards Heath*).
Hurlston, Frank Arnold (*Harborne*).
Irving, Stanley Carrick (*Croydon, Surrey*).
Johnson, Benjamin Marrows (*Healing*).
Jones, Ivor Roderick Lloyd (*West Bridgford*).
Newton, Harry Owen (*Hull*).
Page, Robert Sidney John (*Newport, Mon.*).
Parnell, Albert John (*Cranwell*).
Plowman, Frank (*Middlesbrough*).
Reed, Robert Edwin (*London*).
Sheppard, Cyril Edward (*London*).
Varcoe, Kingsley John (*Rochford, Essex*).

Passed Part II only

Burgess, Alfred John (*Formby*).
Dennis, Harry Pollard (*Birkenhead*).
Hyslop, Thomas (*Johnstone*).
Morison, John William (*Sunderland*).
Pagdin, Edward Houlden (*Old Trafford*).
Perry, William Henry (*Handsworth*).
Russell-Stracey, Patrick Henry Andrew (*Barking*).
Wood, Samuel Robert (*Manchester*).

PREMIUMS

In addition to the Premiums mentioned on pages 726 and 727 (vol. 78) of the June issue of the *Journal*, the Council have awarded the following Premiums for papers read before the Students' Sections during the session 1935–36:—

Premiums of the value of £10 *each:*

Author	*Title of Paper*	*Where read*
K. C. Coop, B.Eng.	"Pollution of Suspension-Type Insulators on Overhead Lines"	Leeds
T. D. Oswald, B Sc.	"Lightning"	Newcastle
A. Wilcock	"Multi-Channel Voice-Frequency Telegraphs"	London

Premiums of the value of £5 *each:*

Author	*Title of Paper*	*Where read*
P. Baxter	"Instrument - Testing by means of Phantom Loads"	Manchester
J. R. Bell	"Choice of Motors and Control Gears for Industrial Drives"	Chester
H. Birchenhough	"Single-Line Railway Signalling"	London
J. S. Cliff	"High-Power Switchgear Test-Plants"	Birmingham
G. V. Harrap	"Electricity - Supply Legislation"	Newcastle
W. F. Parker	"Layout and Design of Distribution Systems in Factories"	Liverpool
B. C. Robinson	"Cathode Rays—their Aid to Measurement"	Newcastle
I. S. Scott-Maxwell	"Electrically - driven Rolling-Mills"	Glasgow
C. D. J. Statham	"Colliery Power Problems"	Sheffield
D. Smith	"Carrier-Wave Telephony"	Newcastle
W. S. Thomson, B.E.	"Insulator Testing and Maintenance on Live H.T. Lines"	Birmingham

ACCESSIONS TO THE REFERENCE LIBRARY

[Note.—The books cannot be purchased at the Institution; the names of the publishers and the prices are given only for the convenience of members; (*) denotes that the book is also in the Lending Library.]

Adam, A. T. Wire-drawing and the cold working of steel. 2nd ed. 4to. 160 pp. (London: H. F. and G. Witherby, 1936.) 35*s*. (*)

Agg, T. R., and Foster, W. L. The preparation of engineering reports. 8vo. viii + 192 pp. (New York, London: McGraw-Hill Book Co., Inc., 1935.) 10*s*. 6*d*. (*)

Allen, J. R., and Walker, J. H. Heating and conditioning. Formerly published under the title "Heating and ventilation." 4th ed., with a chapter on "Hot-water heating systems," by F. E. Giesecke. 8vo. vii + 444 pp. (New York, London: McGraw-Hill Book Co., Inc., 1935.) 24*s*. (*)

Ampère, A. M. Correspondence du grand Ampère. Publiée par L. de Launay. Société des Amis d'André-Marie Ampère. 2 vol. la. 8vo. (Paris: Gauthier-Villars, 1936.) 120 *francs*.

Ardenne, M. v. Fernsehempfang. Bau und Betrieb einer Anlage zur Aufnahme des Ultrakurzwellen-Fernsehrundfunks mit Braunscher Röhre. 8vo. 117 pp. (Berlin: Weidmannsche Buchhandlung, 1935.) *RM*. 6.30.

Avery, A. H. Small alternating current motors. sm. 8vo. 51 pp. (London: Percival Marshall and Co., Ltd., 1935.) 1*s*. 6*d*.

Baumeister, T., *Jr*. Fans. 8vo. xi + 241 pp. (New York, London; McGraw-Hill Publishing Co., Ltd., 1935.) 21*s*. (*)

Beeching, R., *A.R.C.S*. Electron diffraction. With a preface by G. P. Thomson. sm. 8vo. viii + 107 pp. (London: Methuen and Co., Ltd., 1936.) 3*s*. (*)

Bellescize, H. de. Les communications radio-électriques. fasc. 1. vi + 98 pp. (Paris: Gauthier-Villars, 1935.) 20 *francs*.

Bhatnagar, S. S., *M.Sc., D.Sc.*, and Mathur, K. N., *M.Sc., D.Sc.* Physical principles and applications of magneto-chemistry. 8vo. xiv + 375 pp. (London: Macmillan and Co., Ltd., 1935.) 21*s*. (*)

Bolton, D. J., *M.Sc*. Electrical engineering economics. A study of the economic use and supply of electricity. 2nd ed. 8vo. xiii + 365 pp. (London: Chapman and Hall, Ltd., 1936.) 21*s*. (*)

Bond, W. N., *M.A., D.Sc*. Probability and random errors. 8vo. viii + 141 pp. (London: Edward Arnold and Co., 1935.) 10*s*. 6*d*. (*)

British Standards Institution. British standard specifications. nos. 156, 160, 168, 231, 438, 672, 683. 8vo. (London: British Standards Institution, 28 Victoria Street, S.W1, 1936.) 2*s*. 2*d*. *each, post free*.

no. 156, for enamelled high-conductivity annealed copper wire. (Rev., June, 1936.)
no. 160, for slate and marble insulating slabs for electric power switchgear up to and including 660 volts, A.C. and D.C. (Rev., May, 1936.)
no. 168, for the electrical performance of industrial electric motors and generators with class A insulation. Rating permitting overloads. (Rev., June, 1936.)
no. 231, for pressboard for electrical purposes (excluding "built-up" pressboard). (Rev., June, 1936.)
no. 438, for cooker control units for use in 2-wire circuits of not more than 250 volts declared pressure. (Rev. June, 1936.)
no. 672, for hard-drawn cadmium-copper solid and stranded circular conductors for overhead power transmission purposes, 1936.
no. 683, for alkaline train-lighting accumulators, 1936.

Bryant, J. M., *M.S*., and Johnson, E. W., *B.S*. Alternating current machinery. 8vo. xix + 790 pp. (New York, London: McGraw-Hill Book Co., Inc., 1935.) 36*s*. (*)

Burnham, T. H. Engineering economics. 3rd ed. 2 vol. 8vo. (London: Sir Isaac Pitman and Sons, Ltd., 1935.) 8*s*. 6*d*. *per volume*. (*)

book 1, Elements of industrial organization and management. xiii + 280 pp.
book 2, Works organization and management, x + 312 pp.

——Works management education, with special reference to the Case System. With a foreword by E. S. Byng. 8vo. xi + 91 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1933.) 7*s*. 6*d*. (*)

Caldwell, P. S. Gas and oil engines: running and maintenance. sm. 8vo. x + 125 pp. (London: Constable and Co., Ltd., 1925.) 3*s*. 6*d*.

Chapple, H. J. B. Popular television; up-to-date principles and practice explained in simple language. xiii + 112 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1935.) 2*s*. 6*d*. (*)

Clayton, A. E., *D.Sc.(Eng.)*, and Shelley, H. J. Elementary electrical engineering. 2nd ed. 8vo. xi + 462 pp. (London: Longmans, Green and Co., Ltd., 1935.) 7*s*. 6*d*. (*)

Cocking, W. T. Wireless servicing manual. sm. 8vo. x + 213 pp. (London: Iliffe and Sons, Ltd., 1936.) 5*s*. (*)

Cook, A. L., *M.S*. Elements of electrical engineering. A textbook of principles and practice. 3rd. ed. 8vo. x + 603 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1935.) 20*s*. (*)

Creighton, H. J., and Koehler, W. A. Principles and applications of electrochemistry. 2 vol. (vol. 1., 3rd ed.) 8vo. xviii + 502, xiv + 505 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1935.) (*)

vol. 1, Principles, by H. J. Creighton. 20*s*.
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Crook, W. E. Wireless telegraphy: notes for students. (Covering the Postmaster-General's air licence for W/T operators.) 8vo. vii + 189 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1935.) 7*s*. 6*d*. (*)

Curchod, A. Memento d'électrotechnique. tom. 3. xviii + 655 pp. tom. 4. xix + 831 pp. Index alphabetique des quatres tomes. 101 pp. 8vo. (Paris: Dunod, 1934–35.)

tome 3, Réseaux de distribution d'energie électrique. 128 *francs*.
tome 4, Applications de l'électricité. 136 *francs*.

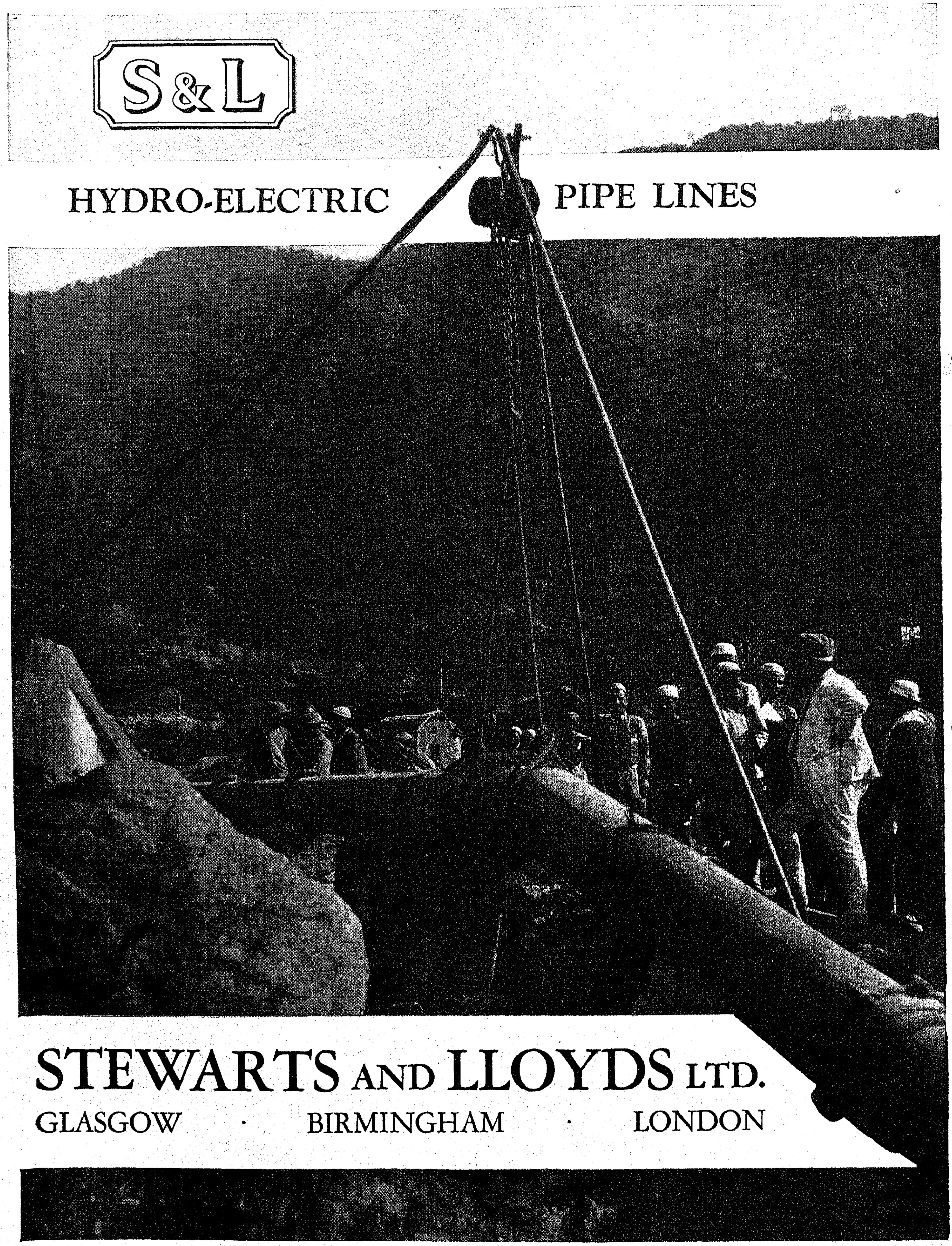
Dent, A. G. H. Management, planning and control. With a foreword by Sir G. Beharrell. 8vo. xxii + 333 pp. (London: Gee and Co. (Publishers), Ltd., 1935.) 10*s*. 6*d*. (*)

Dickinson, H. W. James Watt, craftsman and engineer. 8vo. xvi + 207 pp. (Cambridge: University Press, 1935.) 10*s*. 6*d*. (*)

Doherty, R. E., and Keller, E. G., *M.S., Ph.D.* Mathematics of modern engineering. vol. 1. 8vo. xxi + 314 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1936.) 17*s*. 6*d*. (*)

Dole, M., *Ph.D*. Principles of experimental and theoretical electrochemistry. 8vo. xiii + 549 pp. (McGraw-Hill Book Co., Inc., 1935.) 30*s*. (*)

Dyson, F. Principles of mechanism. 2nd ed. 8vo. vi + 323 pp. (London: Oxford University Press, 1935.) 12*s*. (*)



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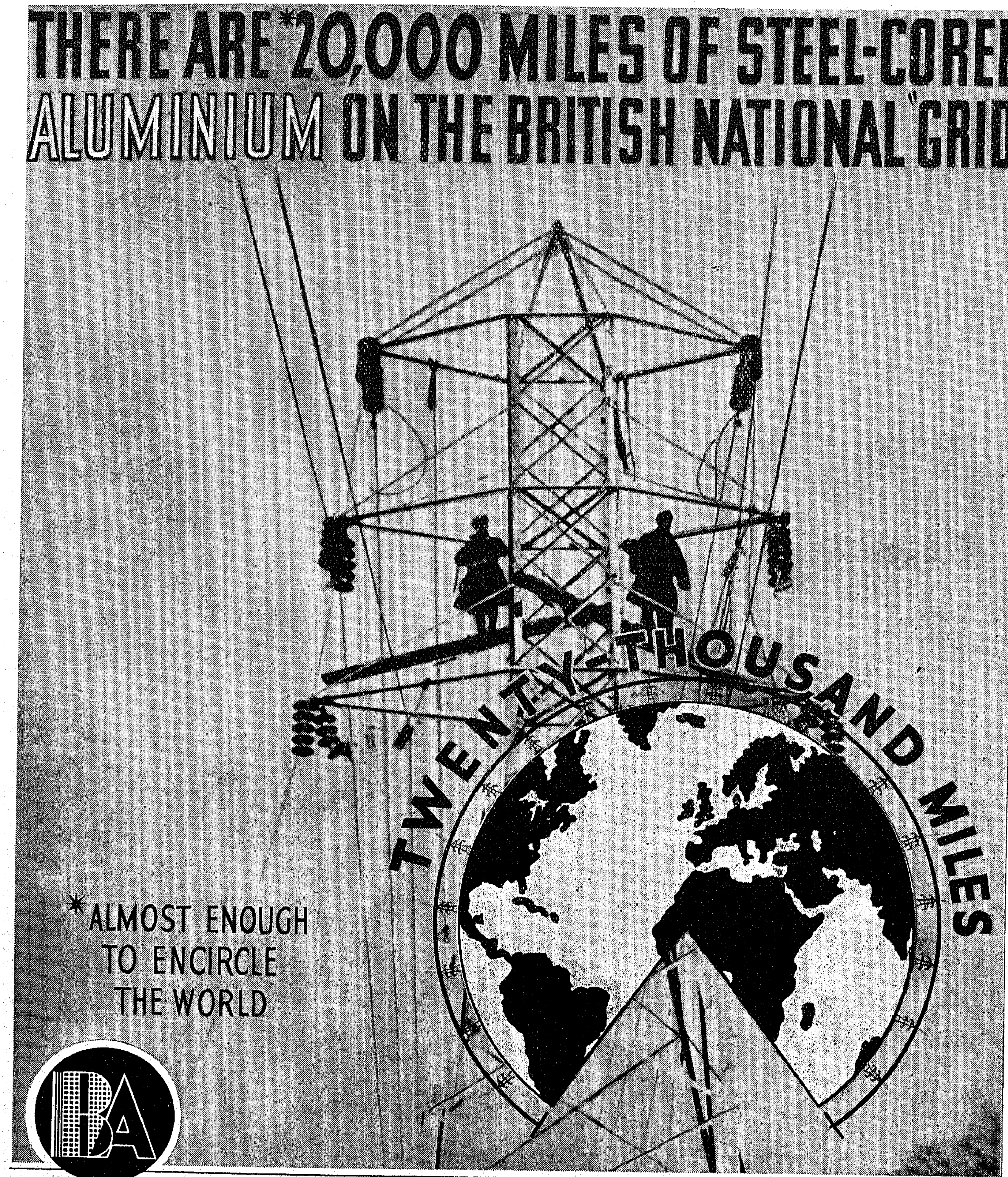
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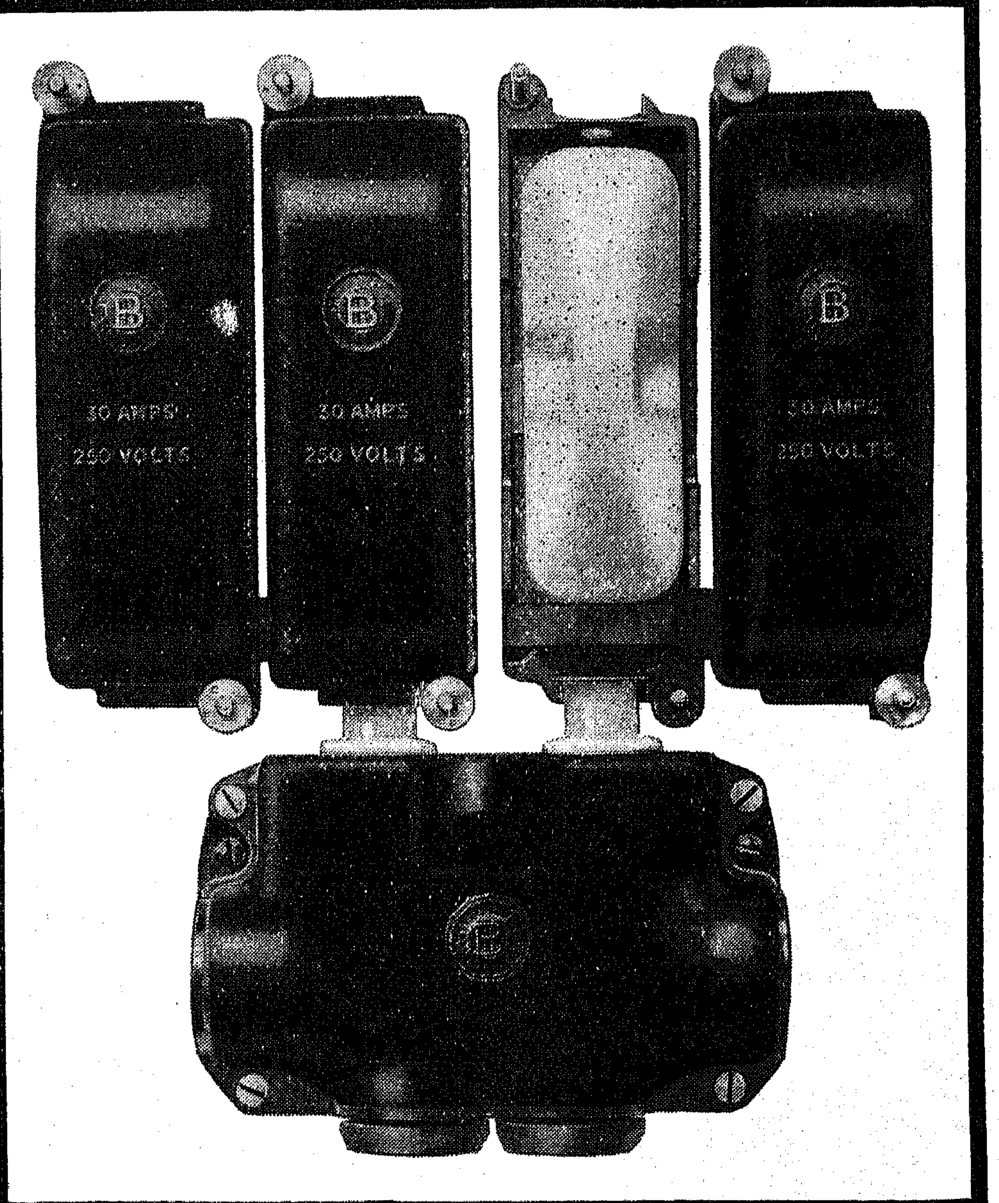

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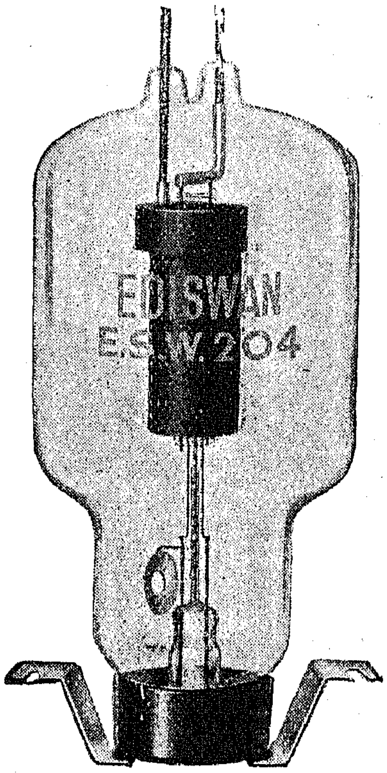

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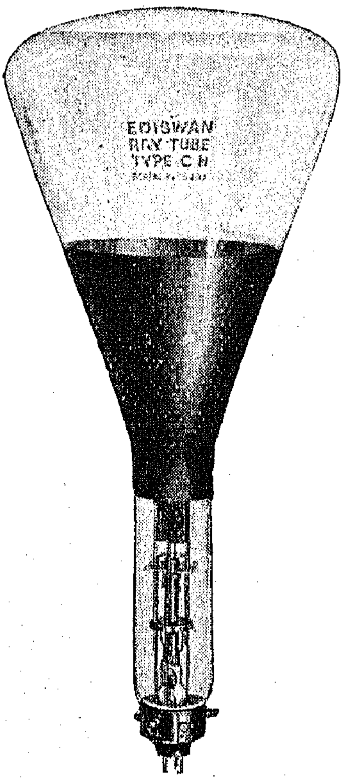

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